Fabrizio D'Errico · Maurizio Dalla Casa

The Sequence of Event Analysis in Criminal Trials

Scientific Proofs for Tracking Criminal Liabilities in Complex Accidents and Disasters

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Preface

On 29 June 2009, the most serious railway accident involving civilian mortalities that has ever occurred in peace time in Italy took place just outside the station of Viareggio. At 11:50 p.m. the first in a convoy of 14 railroad tanks containing liquid petroleum gas (LPG) derailed because the second axle of the first truck snapped free, which then caused the derailment of the goods train Trecate–Gricignano in transit along the fourth line of Viareggio station at a speed of about 94 km/h. The passenger platform of the fourth line stopped the first railroad tank from falling inside the station and this kept all the trucks attached to it in an upright position for the moment, which was a stroke of luck inside the wider tragedy as it limited the damage caused to some extent. However, once the convoy went beyond the platform, the first tank fell on its left hand side bringing down some other trucks in its trail.

The first tank continued on its way sliding along the ground on its side and it struck against an element of the railway line and was torn open, thus allowing the entire load of LPG contained in it to escape into the air. Inside the container LPG is in a liquid state, but, having been freed into the atmosphere, it changes into a heavy gas which floats low in the air along the ground and can filter under a door. Few minutes after the dispersion of the load the raging inferno began which caused the death of 32 people. None of the victims were on board the train.

On 2 November 2011, after two years of intense investigations the case appeared in court for the three-day pre-trial hearings on special evidence. However, when this pre-trial conference was wound up on 4 November a problem of method had appeared.

Its closing was dramatic. Family members of the victims of the tragedy were present in the courtroom.

It is enough to read the conclusions of the Prosecutor given here in adapted form:

> In accordance with Article 231 of the Italian Code of Criminal Procedure, I request the substitution of the forensic experts on account of their negligence [. . .].
>
> We are speaking here about 32 people who have met their deaths.
>
> We do not embrace any particular theory and we welcome anyone who says that we have made mistakes because we want our backs to be put up against the wall!

The premises are false and our duty to the truth whatever implications that may have on the trial has not been carried out.

No evaluations were even done using the mathematical models that we have acquired after two years or more of work [. . .].

How can we accept a report whose findings are full of holes and replies (from the expert witnesses, editor's note) which so clearly seek merely to avoid the objections which have been brought up by the victims' lawyers?

I quote (the Public Prosecutor cites the expert witnesses named by the Judge, editor's note): 'We have not included the evaluations because we rejected them'.

[. . .] Your Honor, it is as if we were to convict someone because he looks vaguely like the person who carried out the robbery and we do not even stop to think that in that moment he was not to be found in the town of Lucca, for example, where the robbery took place but was elsewhere.

If we were not to allow that a DNA test has not cleared him of all accusation how would we go about sentencing him.

Would we sentence him because he is a 'look-alike'?

A look alike!

Nothing is certain here, everything is up in the air, nothing has been demonstrated. What universal or natural law can justify the event?

None of us is in love with a thesis, but we want to be defeated. We know very well that during a penal trial the consultant's work can condition that of the judge and put his conclusions on the fast track. In this case, we cannot allow that to happen.

We must leave no doubts.

We cannot leave even the shadow of a doubt.

Two contrasting technical hypothesis concerning the reconstruction of the events is the possible worst thing that can happen to a judge during a trial. Different positions immediately trigger animated discussions and excited disputes between the expert witnesses that frequently leave the non-technical people—lawyers, prosecutors, judge—excluded from the scrutiny. Mostly, technical consultants and expert witnesses talk to each other in a language that is virtually incomprehensible, while the judge has no alternative but to ask them a direct question the reply to which will, in one way or another, relieve him of the burden of having to make a decision on questions he scarcely knows about: "what is, in your opinion, the probability that what you maintain did actually occur?"

The problems inherent in the reconstruction of industrial accidents should of course be set out in a completely different way. The judge, the public prosecutor and the lawyer need to be put into a position where they can understand and be able to formulate their own understanding of the evidence, which can be guaranteed by the correct scientific reasoning of the expert witness. The expert witness must not, therefore, concentrate on the "details," interpreting them as he sees fit and he must never, just because there is a single piece of evidence that seems to move in the direction of a hypothesis that he has formulated, consciously or unconsciously neglect others that would clearly refute it.

In addition to this age-old dilemma concerning the incomprehensible and often irrefutable statements set forth by many expert witnesses in the law courts, there is another problem that needs to be faced. This derives specifically from the great confusion that is created whenever a lawyer speaks in terms of a causal link

between behavior and event (having clear in his mind Article 40 of the Italian Code of Criminal Procedure), while the expert witness is speaking in terms of the causal relationship between evidence and event, initially, and then between connected events.

These two approaches, which we will distinguish as judicial (the first) and evidential (the second) reasoning must in some way be held separate to avoid dangerous mutations, but will also have to come together sooner or later to reach the proof about a fact or an event, proof of the anti-juridical behavior of the offender, who is to be held guilty and punished.

These are what we could call the missing gaps concerning the reconstruction of criminal liability in the field of industrial accidents, and, starting from there, this book sets out to take the reader not used to technical and scientific themes by the hand and map out the "construction" of a method to be used whenever he needs to evaluate the quality, the effectiveness and above all the precision of the work carried out by the expert witness. At the same time, however, the method proposed in this book also helps the reader to understand that he cannot expect the expert witness to think in terms of the causal link between behavior and event—that is, at least, until the moment is right.

This book is set out in two parts.

The first is called: "Judicial thinking and evidence in the field of industrial accidents," and it is divided into four chapters.

In the first chapter we lay down the foundations of how to reason from evidence, beginning, initially, from the idea of demonstration, verification, guarantee and the level of knowledge that can be acquired based on the use of the three possible forms of reasoning (deductive, inductive and abductive). We will also discuss the concepts of probability and uncertainty connected with the use of reasoning methods that are purely inductive. Particular analogies are outlined between the methods applied in the analysis of a crime scene and those that are used in the gathering and analysis of information on the scene of an accident.

In Chap. 2 we make a brief introduction to the causal relationships that allows judge, as well as prosecutor and attorney in their own supporting roles, to reconstruct under correct enlarged view the penal responsibility in the field of industrial accidents that involve several responsible people who are persons in charged for complex and multilevel interconnected decision making process.

In Chap. 3 we introduce the principles from which it is possible to establish whether an effect—to put it simply—has been determined by a particular cause. The first thing we have to do here is to establish what we mean in scientific terms when we say that "something is the cause of something else." This allows the reader to begin at least to understand the concept of phenomenological or natural cause which connects two events in an accidental chain that has been correctly reconstructed. We will be reflecting therefore on potentialities—too frequently unexpressed—that derive from the correct application of scientific laws in the reconstruction of a happening. We will be able to see thus that, although it is almost a necessity to talk in terms of probability in the field of forensic pathology, in that the human machine is so complicated that we can never be fully certain about the

phenomena involved—the situation is totally different nevertheless in the field of industrial accidents.

As far as accidents are concerned, whether we are talking of an industrial plant, a machine or a means of transport, what "regulates" the system under study are "quite simply" the laws of physics, of chemistry or, on a specialized level, classical mechanics, metallurgy and the science of materials, and so on. We have to try to clarify, therefore, what is meant by scientific method, which, when it is correctly carried out, is the only process able to construct scientific proof, that is to say the only type of proof which is in itself "beyond all reasonable doubt." We will see the enormous difference between a mere piece of experimental evidence (which is defined as "proof" to the extent that it is erroneously considered as such even in juridical language) and the real scientific proof in itself. We will ascertain that it is frequently just such an absence of scientific method that results in having to interpret the results of a scientific test with a statistical approach or inferences drawn from "probability theory" (in jurisprudence often called Bayesian Inference) even where there is absolutely no need to do so.

All this leads the reader to Chap. 4, where we take up again the concepts introduced in Chap. 1 about the way of thinking used in the scientific field. Here, we demonstrate that the reconstruction of an accident, although it might be logically coherent, may not be consistent with the facts. This happens whenever we reconstruct a complex accident without regard for a rigorous scientific method, for it is that alone which by its intrinsic nature can guarantee the truth of the reconstruction of the facts because it is expandable and verifiable.

We underline the importance to be found in analyzing the "traces" that the *system* under study leaves as it interacts with the surrounding environment; how it is from this that we move on to infer what took place in the reality of the facts. We will show how valuable such traces can be when they are numerous and correctly interpreted as effects of a particular phenomenon.

Once this fundamental concept has been grasped we can finally be able to move on to the analysis of an accident using a Sequence of Event Analysis or SEA. We can see how, by applying a sort of backtracking analysis, the expert is able to extract from the available *traces* all the information—generally inaccessible to those not expert in the subject—which allow him to interpret such *traces* as the effects of precise phenomena.

Based on the iterative three-phase method as introduced in Chap. 3 we will see how it is possible—starting from an interpretation of the traces—to reconstruct a logically coherent sequence of "key events." At this point the sequence of events needs to be counter-verified so it can reach the superior status of a sequence consistent with the facts, that is to say the only true sequence as against those that are coherent or logically possible.

At the end of Chap. 4 we face the problem of how to (re-)connect the *conduct* of one or more harmful *events*, recognizable in the sequence of *consistent events*, which we have (re-)constructed by the application of a *first level SEA*. We will show that once the first skeleton has been defined (i.e., the first level SEA), it is then

possible correctly to find the origin in each *key event* of the conduct that has influenced it from a causal point of view.

Having reached this position, we need to face another dilemma. That is, what types of subject we have to reconstruct the causal links between conduct and harmful event.

This problem leads the reader towards the second part of the book, called "From the Construction of Scientific Proof to Tracing Responsibility," which contains three chapters.

Chapter 5 takes up the conclusions drawn in the first part of the book and the doubts that came up at the end of Chap. 4 concerning the limits in application of first-level SEA, which are inevitably posited when you are proceeding from the reconstruction of the accident to the subsequent phase of tracing responsibilities. From the *first-level SEA* scheme we need to pass on to another scheme complete with a further level of analysis, which we will call *level of conduct*. However, before we understand the details of the *level of conduct* the reader needs to get used to the idea of *system failure*. For this purpose, we have to deal here with a theme that has been introduced only recently into the literature on industrial accidents, known as *organizational accidents*. Beginning with the theories about accidents that were valid in the 1950s first and then the 1970s, we have to focus on what has been put forward since the 1990s concerning the analysis of disasters as a consequence of errors or failures distributed on three different levels of organization: *active failures* (or failures of the "last link in the chain"), *organizational failures* and *inter-organizational failures*.

As examples we have to examine three serious accidents which took place in civil aviation and which are considered fundamental in the literature on organizational accidents.

The three different levels of system failure described in Chap. 5 are therefore formulated in Chap. 6 as the three sub-levels of conduct that complete the multi-level SEA analysis to verify the main conclusions of the investigative commission.

Finally, Chap. 7 sets out to practice the method learnt in previous chapters, by discussion of two real cases authors faced and solved with SEA approach supported by tri-dimensional graphic dynamic reconstruction of the accident.

The conclusions drawn in this book are made as a contribution towards the solution of doubts and false myths concerning the application of science in the field of forensics. If it is evident today that these are already interpreted as techniques able to come up with precious proof, it is equally true as well that, by applying the right methods, we will be able—at least when limiting ourselves to the analysis of industrial accidents—to evaluate when and if our reconstruction of the facts goes beyond all reasonable doubt.

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Part I
On Judicial and Evidential Reasoning in the Field of Industrial Accidents

Chapter 1
On Judicial and Evidential Reasoning in the Field of Industrial Accidents

Introduction

The problem which will lead us through all seven chapters of this book sets off here with a forceful metaphor: the crime itself is like a building that has collapsed before the trial. The public prosecutor has to rebuild it as it was before and the judge has to evaluate the conformity of this to the original. If he is lucky, the public prosecutor finds the ground, the cement, the bricks and the nails. But that is clearly not enough: to build or rebuild a house you need a plan. This plan is the hypothesis. But what *hypothesis* are we talking about?

It is clear, the evidential structure moves from the *reconstruction of the happening*. We can state more generally that the *hypothesis* often comes out of a relevant effect that *moves the inquiry* and proceeds to the search for and gathering of the sets of elements and information that consent us to represent the happening in its causal dynamics.

These are still just a few lines, but some few key words in italics here and there just above trace for the reader the whole or almost the whole supporting structure as regards reasoning from evidence, whose purpose is the verification of the truth of the facts initially and then of responsibilities.

If we put the basic concepts we have set out above into the right order, in the criminal field the verification of responsibility hinges on the principle that there is to begin with a legally relevant fact from a criminal point of view that is attributable to the conduct of a subject who has acted against the law in an blameworthy way.

In Chap. 2 that follows we begin to face the problem of verifying responsibility, here introduced only briefly. This is a process structured from a way of thinking that we will define as juridical. The fact that there is a crime can be given shape only based on a harmful event on the one hand in the presence of anti-juridical behavior on the other, and by the causal relationship between them both.

Of course these concepts are absolutely clear to any criminal lawyer, in that they are the basic "instruments" that he has at his disposition on which he will have to

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F. D'Errico, M. Dalla Casa, *The Sequence of Event Analysis in Criminal Trials*,
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base his defense or prosecution of the accused. The two terms, *behavior* and *harmful event* need to be connected as the elements of an "equation" constructed based on a logical framework of this type: "if behavior X [*is true*] then event Y [*is true*]."[1]

We will learn in next chapters how to set the determination of concurrent causes and the "method" by which they can be identified. For now, it is enough to know that we not only have instruments of this kind capable of analyzing the causal relationship between behavior and harmful event, but that they are also very effective.

The type of juridical reasoning that we have been speaking about so far, carried out to ascertain responsibility, becomes more complicated in concrete cases when we ask ourselves how we can be certain beyond all reasonable doubt that:

1) the conduct in question can really be attributed to the accused
2) such behavior is certainly a cause or a concurrent cause of the concrete harmful event.

If we demonstrated that Person definitely passed through Place B at a *certain time*, it would then be reasonable to suppose that he could not have been *at that time* in Place A as well.

This is, in fact, the framework of the alibi which exonerates Person from having committed the criminal fact.

For example, let us imagine that we are setting off on the search for *traces* confirming the presence of Person in Place B: what could they be? A receipt issued for a hotel room? We could object, however, that an accomplice of Person's, who bears a resemblance to him, gave the *receptionist* a well-forged document containing false personal details. Now, the question could be resolved by looking at the film footage in the hotel's video cameras. On the other hand, however, we would still be in some doubt as to whether the accomplice might have carefully disguised himself to trick the eye of the video camera.

The investigator does not want to give in, but he understands that he needs to increase the level of credibility of his hypothesis. He thinks—if it is true that Person travelled from Place B to Place A on board an airplane (there is a boarding card given to him which testifies to this), it will surely be possible to verify the movements of the "true" Person through the airports of departure and arrival. The investigator knows that the airport of arrival is outside the European Union in the USA. From this information he *formulates a hypothesis* which satisfies him more in terms of its *degree of certainty*, and he decides to carry out a *test* of verification. His hypothesis is that on his arrival in the USA, Person (or a simulator of Person) must have passed the US Public Health Immigration & Naturalization controls. Here the authorities will not only have checked his passport with much greater care than the

[1] Note that, in logic, the structure of a conditional proposition does not need to specify that it "is true"; that is to say the same phrase would normally be written: "If X, then Y" with the implicit consideration that both event X and event Y are true. Nevertheless, to avoid any incomprehension we presently prefer to integrate the text by adding the specific unnecessary phrase "is true."

receptionist at the hotel (they are far more competent in deciding whether a passport has been forged), but above all the investigator also knows that an electronic *display* will have recorded his fingerprints. This recording is still recorded in the data archive of the computer's memory, which is available for his use from his American colleagues: all he has to do is verify them.

In this simple example, we see an increase both in the number of traces that have to be collected to broaden as far as is possible the *hypothesis* to be verified and also the degree of certainty sought-after to validate the hypothesis by using a reliable test.

However it is just as evident that the process the investigator sets up cannot leave the reconstruction of events (Person's movements) out of consideration: these are organized into a repeatedly (re-)formulated sequence which becomes increasingly refined as it is put into precise chronological order in agreement with a precise spatial organization (e.g., Person set off *from the hotel to the airport* at *such and such a time* and on that *given day*). This sequence needs to be proven based on the correct interpretation[2] of the traces that have been collected (i.e., the elements analyzed by the expert that identify Person's presence), which must all be corroborated by a high degree of precision and proof.

We will have an in-depth look at this last aspect in Chap. 4: for now it is enough to consider that the way of reasoning we have just described, which we could call *evidentiary* to distinguish it from its *judicial* counterpart, is the type of process that is set up to (re-) assemble brick after brick the "building" based on its "plan" which is unknown at the beginning of the inquiry.

This is another all-important concept that we will be following through the book: to carry out our job, which is to ascertain who is responsible, we need to first reconstruct the happening, i.e., try to set in line the events that from now on we will call key events.

This reconstruction of the events is a very delicate affair: as we have seen in the simple example above, from the correct identification of the sequence of events—on condition that it can be *proven*—we may or may not be able to derive strong implications about the responsibility of a particular individual.

To get a technical understanding of what the reconstruction of an incident really means, K. L. Carper[3] explains that it is a process directed towards the determination of the order and timing of important events that have led in the direction of the final event.

---

[2] We speak about the interpretation and not merely the collection of traces because as they grow in complexity they will need an agent capable of interpreting them, the field expert, who will be able to give them a consistent explanation. This is the delicate passage that enables us to turn the traces into evidence. If you think about the simple example of Person's fingerprints or, even more banal, the manufacture of his passport, you will see that both the fingerprint and the photograph on the passport are to be considered elements that can testify Person's "presence" in a place. However, only an expert witness is able to evaluate potential efforts in falsification on one or the other element.

[3] K. L. Carper ed., Forensic Engineering, 2nd ed., CRC Press, Boca Raton 2001.

In carrying out this type of analysis, the investigator usually works backwards from the moment of the incident itself: what the investigator (or in this case, the forensic engineer) has to determine is the sequence of events that took place starting from a definite starting event, or trigger event, leading to a definite event called final event representing the end of the temporal line describing the incident. All this is done basing the work essentially and exclusively on the comprehension of the facts.

In the same way, R. K. Noon[4] remarks that the conclusions of an inquiry using the techniques of forensic engineering should be carried out basing the efforts on the facts of the analysis and not on mere conjectures. If the facts have been set out in a logical, systematic way, the conclusions should be almost evident *in themselves*.

Conclusions based on other conclusions or hypotheses formulated in their turn on a few selected facts or very general principles are to be considered merely "a house of cards."

The Idea of Demonstration and the Three Forms of Reasoning

Part of the process through which we acquire any type of knowledge is by our power of reasoning. There are many ways by which we reason and debate with ourselves to arrive at certain conclusions, and some of these processes seem more certain and convincing than others. Certain approaches to thought seem to show that in cases where particular preconditions are accepted a distinct conclusion must necessarily follow. Such a way of thinking is called *deductive*. Correct deductive reasoning shows that when the preconditions are true, the conclusions are as well. Deductive reasoning is historically connected to Aristotelian syllogism, which is, in fact, the form of reasoning that accompanied our research and discovery of the world for 2000 years.

To clarify what we mean by valid deductive reasoning it will be enough to refer to a famous example:

All men are mortal (*main premise*)
Socrates is a man (*minor premise*)
Socrates is mortal (*conclusion*)

As will be clear, the truth of the conclusion is guaranteed by the truth of the premises. In other words, moving from *universally valid statements*, i.e., the two main and the minor premise in Aristotle's syllogism, the conclusion arrived at is certainly true. Based on these presuppositions, valid deductive reasoning always gives a guarantee: in other words, we can be sure that if the premises are true, then the conclusion will be true as well. This is a characteristic of mathematical thought

[4] R. K. Noon, Forensic Engineering Investigation, CRC Press, Boca Raton 2001.

which is particularly rich in Euclid's formulations: in the field of mathematics[5] or geometry (which by tradition has been handed down from the ancient Greeks) this method is also called axiomatic in that by starting off from statements that are certainly true it leads on to the elaboration of complex *theories*.[6]

In other words, by using deductive reasoning it is not possible to extend the properties or characteristics of an element, but only to "verify" whether this element is equipped with the particularities that have been characterized in the two premises that were previously formulated.[7] Yet, does all this mean that the reasoning powers of the human mind can never arrive at a new level of consciousness with respect to that which has been supplied by the premises? Fortunately for the history of scientific theory that is not the case.

There are, in fact, other forms of reasoning that are not deductive.

In some cases we discuss matters, reaching conclusions made based on a certain number of observations or the elaboration of data. These forms of reasoning are called inductive and they are carried out following inferences that proceed in the opposite sense to those that are deductive. To get a better grasp of what this consists in, let us consider the typical scheme of an inductive inference:

I saw a crow and it was black
I saw a second crow and it was black
I saw the umpteenth crow and it was black
. . . . . .
Crows are probably black

---

[5] Notice that we are talking here of mathematical methods which are not to be confused with scientific methods, even if we consider that mathematics permeates any enquiry of a scientific nature. It is obvious that all scientific disciplines have to do with "laws" that are formulated more often than not using instruments of a mathematical nature (it is enough to think of the universal laws of gravitation elaborated by Newton). Later in the book we will attempt to clarify the subtle distinction that exists between mathematical and scientific methods. To do that, however, we need to first introduce a new form of reasoning which is not simply deductive.

[6] Euclid begins from an axiomatic system based on *definitions* (e.g., "a point is that which has no parts"; "a line is length without width," etc.) *common notions* (e.g., "things which equal the same thing equal one another") which are not directly connected with geometry, and *postulates* (e.g., "postulate: you can conduct a straight line from one point to any other point") which, instead, have to do with geometry. On the basis of this axiomatic system organized around carefully chosen *definitions*, *common notions* and *postulates*, Euclid deduces the geometrical *theories* that are still studied in High Schools today.

[7] George Boole 1815–1864, logician and mathematician is considered to be the founder of mathematical logics. Boole was the first to study logical deductions formulated in natural language through a formal language called, in fact, Boole's Algebraic Language or Boolean Algebra. Even easier to remember are the "symbols" introduced by Eulero in 1787 (L. Eulero, Letters to a German Princess, Ferres, Naples, 1787) to carry out logical "operations" in a symbolic but easily intuitive fashion. These are the "rings" inside which the "sets" are represented, i.e., classes of types with determined characteristics. For example, if we are to represent the main premise in Aristotle's syllogism "all men are mortal" we would draw the ring representing the class "men" in a larger circle representing the class "mortal beings." The minor premise "Socrates is a man" means in the theory of sets that "Socrates" is an element of the set "men." It follows that because he is certainly included inside the wider circle, we can deduce that the element Socrates is equipped with the same particularities as the set "mortal beings": thus he is himself unequivocally mortal.

As you can see in this simple example inductive reasoning introduces a principle: the level of final knowledge is amplified with respect to the information (acquired by observation) contained in the premise. In other words, the conclusion expects to formulate a general *rule* from which to be able to predict the *result* of our next *observation*: the crow that we will see will (probably) be black.

Because of this particular structure of inductive reasoning it came about in the past that Bacon and Hume identified it "the Method" with which to conduct a scientific observation. Let us say at once that this very reductive vision of the scientific method has been superseded by philosophers of science (first, Popper and Pierce) and by twentieth century scientists (Mach, Einstein, Hertz, Kraft), who brought to light the errors and the conceptual limits of the *inductivists* of the Bacon and Hume type.

Going back to our example of the black crows, we notice that the *prediction* about the next result cannot have the character of certainty: this is, in any case, already specified in the conclusion: all crows are probably black. That is to say, from the information that we have gathered nothing forbids us from thinking that we might see one day a particularly rare type of white crow or spotted crow or crow of any other color.

It is a good thing to clarify that, although it is true we had to wait for the twentieth century to reach the conclusion that neither of the two proposed reasoning schemes is *exclusively* in possession of the peculiarities of scientific reasoning, this does not mean that scientific reasoning had not seen the light until that moment. A good three centuries before that, the Pisan Galileo Galilei (1564–1642) had already developed it for the first time, and the Englishman Isaac Newton (1642–1727) had made further great improvements on it.

The dilemma was resolved when someone noticed that the scientific method is based on both of the methods applied: they are, however, applied as two "phases" of a cognitive process that is more complex and articulated, comprising a third form of reasoning that we have not as yet introduced. The declination of this further form of reasoning was the key to getting beyond the deadlock in the philosophical debate over the nature of the scientific method and arriving finally to a turning point. Before looking in any detail at the third scheme of logical reasoning, we will first summarize the reciprocal positions that were so opposed one to the other that they ended up creating a stalemate. In this way we will be better able to understand their various nuances.

– **Deductive reasoning** gives us the certainty of the conclusion: this is an undeniable advantage for the scientist. On the other hand it is not possible to amplify our degree of knowledge of things beyond the level that is already declared in the premise from which the inquiry begins;
– **Inductive reasoning** allows us to elevate our degree of knowledge with respect to the simple observations carried out. On the other hand, we are at the mercy of the uncertainty of these conclusions. The result can only be probable, never certain: in the scientific field this is not enough.

Among the many illustrious scientists that took part in the debate, Albert Einstein expressed himself with clarity on the fact that theories "cannot be obtained through a distillation of experiences that have been lived using any inductive method, but only through free invention", specifying in support of his theory that:

> The great steps forward in our knowledge of nature have been made following a path that is diametrically opposed to the one followed by induction. An intuitive concept (*Erfassung*) concerning the essential nature of a large complex of things brings the researcher to the **proposal** (*Aufstellung*) of a hypothetical **principle** (*Gundgesetz*) or a number of principles of that type. From the principle (system of axioms) he **deduces** in a purely **logical – deductive** way the **consequences** in the most complete manner possible. These consequences are extractable from the beginning often through developments and boring calculations, and are then compared with the experiences, thus supplying the criteria of **justification** (*Berechtigung*) for the admitted principle. The principle (axioms) and the consequences together form what is called a 'theory'. Every educated person knows that the biggest advances in our knowledge of nature – for example, Newton's theory of gravitation, thermodynamics, the kinetic theory of gasses, modern electrodynamics, etc., – have all originated in this way [. . .] **The researcher, therefore, always begins with the facts** [. . .] But he does not arrive at his theoretical system in a methodical, inductive way; rather, he gets nearer to the facts by making intuitive choices between thinkable theories based on axioms. A theory can be recognized as wrong when there is a logical error in its deductions, or it can be recognized as inadequate when a fact is not in agreement with one of its consequences.[8]

Einstein's text delineates in clear strokes the cognitive processes on which the scientific method is based: we begin with the *facts* elaborated by using simple observations (Galileo, for example, observed the movements of the planets),[9] from which we conjecture a hypothesis (the *principle* in Einstein's terms) which can give a causal explanation of the observations that have been made.

The researcher reasons in this way, in other words: "if the law that has been hypothetically presumed (or the *principle*, in Einstein's terms) turns out to be true, then the observations carried out would be well-explained."

This is a way of reasoning that is profoundly different from the two earlier types that we have classified: as distinct from deductive reasoning it does not give any guarantee about the truth of the conclusions but it allows for the addition of knowledge to the premises and in this sense is similar to *induction*.

As distinct from induction, this particular form of reasoning goes beyond a general conclusion: starting off from the simple sequence of a series of observations (as we have seen in the example of the black crows) we arrive to the formulation of a hypothesis about the causes by which we can explain the observations themselves. Sometime before Einstein and the other illustrious scientists that gave life to this debate, Charles Sanders Peirce, philosopher of scientific thought and method and the father of American pragmatism, called this form of reasoning *abduction* to

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[8] A. Einsten, Induktion und Deduktion in der Physik, in Berliner Tageblatt, 25 December 1919.

[9] And here again Galileo constructed a system, the inclined plane (which we will discuss later in greater detail in Chap. 3) to carry out experiments in a simplified, controlled "environment," to interpret the results and thus to produce inferences on the *observations*.

distinguish it from both *induction* and *deduction*. In a famous example,[10] Peirce explains the difference between deductive, inductive and abductive reasoning. What follows is an adapted form of the text destined to make a big change in the debate on the foundations of modern scientific thought[11]:

> [. . .] If, from a bag of beans for which we know that 2/3 are white, we take one at random, it is deductive inference that this bean is probably white, the probability being 2/3. We have, in effect, the following syllogism:
>
> Rule. – The beans in this bag are 2/3 white
> Case. – These beans has been drawn in such a way that in the long run the relative number of white beans so drawn would be equal to the relative number in the bag.
> Result. – This bean has been drawn in such a way that in the long run it would be turn out white 2/3 of the time.
>
> If instead of drawing one bean we draw a handful at random and conclude that about 2/3 of the handful are probably white, the reasoning is of same sort. If, however, not knowing what proportion of white beans there are in the bag, we draw a handful at random and, finding 2/3 of the beans in the handful white, conclude that about 2/3 of those in the bag are white, we are rowing up the current of deductive sequence, and are concluding a rule from the observation of a result in a certain case. This is particularly clear when all the handful turn out one color. The induction then is:
>
> These beans were in this bag
> These beans are white
> All the beans in the bag were white
>
> Which is but an inversion of deductive syllogism.
>
> Rule. – All the beans in this bag were white
> Case. – These beans were in the bag
> Result. – These beans are white
>
> So that induction is the inference of a *rule* from the *case* and *result*.
> But this is not the only way of inverting a deductive syllogism so as to produce a synthetic inference. Suppose I enter a room and there find a number of bags, containing different kinds of beans. On the table there is a handful of white beans; and, after some searching, I find one of the bags containing white beans only. I at once infer as a probability, or as a fair guess, that this handful was taken out of that bag. This sort of inference is called *making and hypothesis*.[12] It is the inference of a *case* from a *rule* and a *result*. We have then:
>
> DEDUCTION
> Rule. – All the beans from this bag are white
> Case. – These beans are from this bag
> Result. – These beans are white

[10] C. S. Peirce, Collected Papers, edited by C. H. Hartshorne and P. P. Weiss, Harvard University Press, Cambridge, 1965.

[11] Cf. the further details in C. S. Peirce, *Deduction, Induction and Hypothesis* in C. S. Peirce, *The Essential Peirce*, edited by N. Houser and C. J. W. Kloesel, Indiana University Press, 1992.

[12] In this text Peirce still uses the word *hypothesis* to formulate the alternative type of reasoning to the classical logical deductive or inductive scheme. In the following manuscripts, he starts to use the word abduction, instead of hypothesis.

INDUCTION
Case. – These beans are from this bag
Result. – These beans are white
Rule. – All the beans from this bag are white

HYPOTHESIS
Rule. – All the beans from this bag are white
Result. – These beans are white
Case. – These beans are from this bag

We, accordingly, classify all inferences as follows:

Inference
Deductive or Analytic | Synthetic
Induction | Hypothesis

> Induction is where we generalize from a number of cases of which something is true, and infer that the same thing is true of a whole class. Or, where we find a certain thing to be true of a certain proportion of cases and infer that it is true of the same proportion of the whole class. Hypothesis is where we find some very curious circumstance, which would be explained by the supposition that it was a case of a certain general rule, and thereupon adopt that supposition. (C.S. Peirce, Deduction, Induction and Hypothesis, 1871)

As will be evident, the conclusion to which we are brought by abductive reasoning as declined by Peirce is probable, not certain. In fact abduction aims at the formulation of a *hypothesis* which is able to explain the **causation** of the case, the observation. It is true that pure induction wishes to formulate a general rule starting out in a similar way from observations; in contrast to abduction, however, it does not interrogate itself about the formulation of some causal law which would make the observations explainable.

An expert in descriptive statistics would say that pure abduction is founded on an acritical analysis of the results. You establish the color of a certain number of beans extracted from a bag about which you only know the total number; you count up, for example, that in your hand two-thirds of these are white beans while the remaining ones are red; you formulate the probable rule that two thirds of the number of beans contained inside the bag is made up of white beans while the remaining third are red.

In the example of the beans on the table, abductive reasoning is not limited to the simple act of "counting": it puts together two pieces of information, the *observation* that a handful of beans on the table are all white, and another piece of objective information (in fact another observation) about the presence of a bag containing only white beans, which is confirmed, in fact, from the information obtained from the label attached to the bag. On the evidence of these two observations you formulate the abstract hypothesis that all the white beans on the table come from

the bag in question, i.e., this constitutes a *cause* of the general *rule*. Yet we could be making a mistake because it might easily be that without us being aware of it, someone may have entered the room with a number of white beans in their hands and have scattered them on the table: in which case it would not be right to infer that the white beans have come from bag with the label on it that says "white beans."

To summarize, we can base *hypotheses* on the foundation of *observations*, i.e., we try to give ourselves the explanation about what we observe under the "mantle" of some general rule.

This is exactly what Einstein was trying to explain: the researcher (looking for a theory) starts off from observations and facts, and from these he tries to construct a theory that can explain these observations. But, exactly as in the case of the beans on the table, he is not yet certain that he has taken all the possibilities into consideration, e.g., the eventuality that, unaware to him, a person has dropped white beans on the table which therefore do not belong to the bag. Now, there is only one step remaining for the researcher to take: to verify if the theory he has formulated by abduction is really valid. How can he do that?

As he is a researcher he has experience with experimentation. Why not, therefore, create an experimental verification that will confirm or confute the theory.

First, however, he needs to know *what* to verify: in that he has formulated a theory that aspires towards becoming a "general rule" (this has been, in fact, the result of the first *abductive* phase of his reasoning), he is now able to predict—by *logical deduction* from such a *rule*—the result of a possible experiment. Seeing as he knows something about what he predicts will be the result, he can now finally set up the final verification *test* because he is aware of what he needs to check. If the result that he has predicted in the abstract is in agreement with the result empirically obtained in his test, his theory will still be valid.

What Do We Mean by Scientific Method?

It should be clear by now that to acquire knowledge the researcher carries out an activity that is neither *deductive,* as the so-called *determinist* wished, nor *inductive* as upheld by the so-called *inductivists*, nor even *abductive*. It is instead an iterative process in such a way that the knowledge we have acquired on each preceding occasion is refined with each re-iteration: the researcher's knowledge includes all three, articulated in precise sequential phases:

a) Formulation of a hypothesis starting off from the observations: this is the first phase that goes beyond a simple **observation** in that it aspires in fact towards the **description** of a particular **phenomenon** (the *case*, in Peirce's terms) through the formulation of a **theory** (the *rule*, in Peirce's terms) that can explain the **observation** that has been made.

   This is the purely **abductive** phase, i.e., the phase during which, for example, Galileo asked himself about the repeatability of a certain phenomenon, the

falling of masses, which he could not explain. In the "Physics" written in the fourth century BC, Aristotle had claimed that the natural state of bodies is a state of rest, that is, the absence of motion, and that any object in movement tends to slow down until it stops unless it is pushed to continue its motion. It was only after nearly 2000 years that Galileo had an intuition about Aristotle's mistake and began to understand that all bodies are gifted with the same freefall acceleration, naturally where the resistance opposed to the mass is negligible (as is the air in the free fall of a body). Galileo understood that there must be a certain independence between the mass and the acceleration of bodies towards the ground, provided that they were free of the attrition created by the air which "contaminated" too greatly the result when he dropped a feather and a metal ball from the leaning tower of Pisa.

b) Once he has formulated his theory, the researcher abstracts the result he would obtain if the theory were to be correct. In fact he makes forecasts which are **logically drawn out by deduction** from the premises, i.e., from the hypothetical theory: this is the logical deductive phase. Galileo had had the intuition that there must be a sort of independence between the acceleration towards the ground of the bodies and their mass itself, but he had to prove it. Above all, he had the hunch that in the next experimental phase he had to eliminate the problem of the air's attrition, which was responsible for the greater deceleration of some bodies with respect to others and which had, therefore, a negative effect on his verification. He concluded that he needed to set up a carefully considered system of corroboration that would be free of "disturbance" effects so that he could carry out clear "measurements" by which to check the hypotheses he had made.

   His deductions brought him to the reasoning phase. Galileo understood that if his theory about the independence of the falling movement of masses was correct[13] then the vertical fall of a body could be considered the extreme *case* in the movement of a mass on a vertical plane (the body falls parallel to the plane and does not touch it even minimally). In this way, in obedience with a principle that he did not even know as yet, it could still hold true that the same movement could come about in the *case* of a plane without attrition which had a certain inclination that could be varied at will. And tilting this plane at angles that were ever greater, he could go from the extreme *case* of a horizontal plane to the extreme *case* of a vertical plane, i.e., the plane that simulated the free fall of the mass. If this is a universally valid principle, Galileo thought, the considerations to be made in the *case* of a plane that was only slightly inclined (for which it is easy to measure the times and the speeds of the balls rolling down without attrition) would be the same as those made if you think of the same balls "rolling without attrition" along a vertical plane.

c) Once he had created the system based on the hypotheses deduced from the theory he had formulated, Galileo began the **experimental verification** phase.

[13] We cannot yet speak of the acceleration of gravity: this will be one of the exceptional results of Galileo's experiments.

> This is the purely inductive phase, during which the hypothesis that has been formulated is tested. It consists in carrying out the experiments and gathering all the possible information. Galileo performed the experiments on the inclined phase and he even worked out a way to measure the rolling-time of the spheres (the stopwatch did not exist in those days). From the measurements that he made and the repeated experiments that he carried out he gained precious information that did not only permit him to verify that the rolling speed is independent of the mass (which in the generalization we discussed above is also the vertical fall of the ball), but he also deduced[14] one of the most important principles of modern science: the **principle of the conservation of energy**, which in this particular case allowed him to formulate the principle of the conservation of the rectilinear movement of a mass.

Now, it is worth introducing another concept that we will talk about in the next chapters: we must not make the mistake of reducing the *scientific method* into a pure *experimental method*. A method can really be called scientific when each of the three phases we have listed are effectively present and predisposed towards acquiring knowledge through the formulation of theories that can and will be verified.

In other words, the three repeated phases (abductive, deductive and inductive) make up the integrating parts of the process and none of them can be eliminated. In fact, if the formulation of the hypothesis were to be missing as the general principle able to explain the repeatability of the process, or if the same conditions had not been fully understood to re-create them in the experimental phase and the results of the experiments were simply to be "read," we might arrive at conclusions that were completely mistaken. These conclusions could then stand in a completely arbitrary and erroneous way as scientific conceptions for the simple fact that an experimental phase has been carried out.

If Galileo had not repeatedly deduced in his theory that the spheres and the plane had to be well-honed and smooth and that the material of which the spheres were made needed to be very hard to limit the phenomena of the dissipation of energy "by movement" (kinetic energy), if, in other words, he had limited himself to "reading" instead of critically interpreting the results of his *tests*, he would not have been able to correct the false beliefs about the movement of bodies that had been promulgated for over 2000 years.

On the debate about the fallibility or the refutability of the scientific method

Moving now from the scientific to the legal field, what do we understand when we speak about universal laws or "unequivocally accepted laws"?

It is a good thing here to introduce a distinction: it is one thing to make a **reconstruction of an accident or a disaster** (to understand what failures have

[14] As we have said, in fact, the scientific method is an iterative cyclical process that results in the progressive acquisition of knowledge.

come about somewhere in man's works of engineering), but **forensic pathology** is a completely different *case*.

When you have to do with the field of forensic medicine the situation becomes complex: the "system" which is the object of your study is not a machine, an industrial plant of a product of engineering. Here you have to do with a human being.

When you consider man's manufactured products, created from centuries of arts and crafts through the use of the intellect in understanding how to exploit universal "forces" and laws[15]—then scientific thought is the point of reference.

Think of all the great leaps forward that technology was able to make in the twentieth century once the principles of thermodynamics were discovered and were capable of explaining, for example, how the pressure exercised by water vapor can be used to produce motor force in a steam engine. During the Industrial Revolution machines were designed based on this newly acquired knowledge: seeing as it was possible to explain the phenomena in the form of universal principles, it had become possible to foresee the "result" of a mechanical or electric[16] system constructed along the lines of those same principles. It was possible to design and construct a certain system, the way it worked could be verified, thus modifying if necessary working conditions to target expectations. An approach, that is to say, which is exactly analogous to what Galileo had carried out centuries before.

It is easy to understand, instead, how in the case of the human body we are moving on completely different grounds: first, the "system" is not "constructed" by man based on laws that he has identified. Man can try to understand these "mechanisms," but they are not easy to work out because we are talking about a complicated system, further obscured by the fact that the phase of scientific "verification" is limited because of ethical questions. These two questions—study of the "machine" system and study of the "human" system—are intrinsically of an entirely different nature.

It is enough to consider, for example, of the experimental phase, i.e., the verifications of the previsions that have been made about the hypothetical effects. These tests are carried out on a limited sample of the population, or, sometimes, on animals, which may resemble, but can never correspond, to the complex system of the human body.

We are fortunate in our case, at least from the point of view of veracity and the degree of certainty that can theoretically be reached: we speak about laws of classical mechanics, of physics and chemistry that can give a causal explanation about all the phenomena in the related scale of observation.

Despite this, a lot of confusion is created when we speak in legal literature of the fallibility of the scientific method, i.e., the uncertainty of the results that can be

[15] It is right to talk in this way about the machines produced by man, at least since the Enlightenment and specifically in the wake of the scientific method introduced by Galileo.

[16] Think of Franklin, Faraday and Hertz's discovery of the principles of electricity, then used by EDISON (1847–1931) and his competitor TESLA (1856–1943) for the electric illumination of streets and houses.

obtained when scientific disciplines are used in gathering evidence. This often happens because people try to interpret, unfortunately in a partial and extremely confused way, the thought of Karl Popper (1902–1994) a twentieth century philosopher and epistemologist, who is considered the greatest philosopher of scientific thought in the modern age. Popper is famous for having introduced the principle in which a *theory* takes on a scientific character only if it is "**falsifiable.**"

The real meaning that Popper attributes to the concept of the falsifiability of a theory is frequently misrepresented in order mistakenly to conclude that the scientific method is to be understood as *in itself* **fallible.**[17] Mostly in fact, two concepts that Popper elaborates and treats separately get mixed up, that is to say "falsifiability" as a method of verification between science and non-science (a demarcation method, to use his terms) and the concept of "fallibility" which he proposed as a convinced *anti-inductivist*.

Popper's concept of falsifiability is set out from arguments that were not new to his contemporaries, such as Einstein for example, Kraft and before them Peirce, whom we have already treated. In a nutshell, Popper introduced the concept of the falsifiability or controllability of a scientific theory because he was tormented by the problem of managing somehow to "demarcate" sciences like physics or chemistry, i.e., sciences that can tolerate measurable and therefore controllable experiments from those which he considered non-sciences, firstly, the psychoanalysis of Freud (1856–1939), of Adler (1870–1937) and social sciences in general.

What attracted Popper's attention in those years was the fact that, in Einstein's case, the famous *theory of relativity* risked being contradicted if the results of the experiments that other experts were carrying out had proven incompatible with what Einstein himself had predicted in the form of deductions that were logically inferred from his theory.

This was a situation that Popper, however hard he tried, could not detect in Freud and Adler's theories, which had the intrinsic capacity to "adapt themselves" to the experiment of "verification." In Popper's judgment, that depended on the fact that the theories of psychoanalysis turned out to be compatible with numerous different types of human behavior which were not suitable to be adopted as confirmation of such theories. In this way, Popper concluded that a theory that does not "risk" turning out to be false subsequent to a verification conducted in a measurable and repeatable way cannot even be considered true.

The second concept to which we wish to refer is the hefty criticism Popper advanced against an "inductivist" approach to formulate a theory. Inferring general principles essentially by observations and experiments[18] is the approach of pure

[17] For greater information on the question, cf. the volume Popper, Karl, Conjectures and Refutations. The Growth of Scientific Knowledge. London and New York: Routledge Classics (2002 [1963]). In any case, we consider that it will be useful here to clarify the general picture of why such a gross mistake is made.

[18] For example: when we observe a particular result obtained in certain examined conditions, we then conclude that every experiment carried out in the same conditions will probably give us the same result.

inductivists,[19] those who, like Bacon and Hume, believed that knowledge of the world could be acquired starting out from pure observation and experimentation. Popper referred to this in his famous example of the black swan: the fact that you have observed a long series of white swans could never confirm the generally valid principle "all swans are white," because you cannot have the absolute certainty that you will never observe a black swan.

This explains why he placed himself with regard to how we acquire our knowledge of the world (i.e., the elaboration of scientific theory) in an approach that was *anti-inductivist*. As far as Popper is concerned observation and experiment are not the starting point: they represent verification techniques through which the theories in "formation" can be controlled and verified; all this, however, always on condition that the theories that have been elaborated live up to the founding principle of Popper's theory, i.e., that they were falsifiable. In the same way as Einstein's theories were at risk, all theories need to be checked, and, if necessary, proven wrong.

When we speak of "falsifiability" as one of Popper's principles we must not, therefore, make the mistake of mixing up the two ways of reasoning that we have been looking at up to now because that often leads to completely mistaken interpretations of his thought, which make it "sound" as if the scientific method is precarious because it is always considered "fallible." It may be true that, once Einstein's theories had been checked (and accepted), it undoubtedly meant that Newton's had been "falsified." Yet we must always remember that Popper's thought refers to the formulation and verification of new scientific theories that lead to the discovery of universal laws: we are not talking about the reconstruction of an event that takes place under the laws of physics on the "observation scale" of classical Newtonian mechanics.

To get a better grasp of this aspect we only have to refer to the concept and the purpose of the scientific method as explained by Feynman, another of Popper's contemporaries.

Different from Popper, Richard Feynman (1918–1988) was not only a philosopher and a scholar of the scientific method, but he was also a physicist, or rather the topmost physicist of the twentieth century, Nobel Prize winner in 1965.

Feynman gained notoriety amongst his fellow Americans because he explained the causes that had led to the disaster of the Space Shuttle Challenger[20] demonstrating his ideas in a simple experiment that he conducted on TV in front of millions of Americans.

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[19] It is a good thing to specify here that we are talking about a pure inductivist approach to distinguish that from the inductive phase which we spoke about earlier when we were explaining the complex type of thinking carried out in the scientific approach. In fact, scientific methods of thinking also include an inductive phase, consisting in the verification (often through experimentation) that the theory formulated during the abductive phase really is valid.

[20] The explosion of the Space Shuttle Challenger, which took place on 28 January 1986 a few seconds after takeoff is without doubt the most serious accident in the history of the American Space Agency.

Feynman says:

> The principle of science, the definition, almost, is the following: *The test of all knowledge is experiment*. Experiment is the sole *judge* of scientific "truth". [. . .] Now, how can an experiment be "wrong"? First, in a trivial way: if something is wrong with the apparatus that you did not notice [. . .] (or) only by being inaccurate. For example, the mass of an object never seems to change: a spinning top has the same weigh as a still one. So a "law" was invented: mass is constant, independent of speed. That "law" is now found to be incorrect (because of the theory Einstein's relativity). Mass is found to increase with velocity, but appreciable increases require velocity near that of light. A *true* law is: if an object moves with a speed of less than one hundred miles a second the mass is constant to within one part in a million. In some such approximate form this is a correct law (Feynman, Lectures on Physics, 1963).

To sum up, when it is our aim to explain an event involving a particle that is moving at a speed proximate to the speed of light, Newton's theory is invalidated by Einstein's in that, on that scale, it effectively fails.

Instead, in cases where you want to reconstruct events and to explain the causation of physical and chemical events that are taking place on a scale that is well under "one hundred and fifty kilometers per second" the laws to which you must refer are precisely those of classical mechanics and they are then "infallible." It is only an inappropriate use of such laws that leads to false conclusions.

The Scientific Method Applied to the Reconstruction of Accidents: The First Foundations of the Scientific Character of Proof

The task entrusted to the forensic engineer who is working on an accident must be that of reconstructing what has happened in agreement with the truth of the facts. To do that, there is no alternative possible to using a working method based on two founding principles:

- It needs progressively to acquire knowledge and refine it as the inquiry examines as many elements as possible;
- It needs to be characterized by some form of guarantee that can assure both the technician himself and the legal worker that the reconstruction of the event effectively respects what really happened.

In other words, every inquiry into an industrial accident must be of a character that is both *amplifying*, in the sense that each element in the inquiry can contribute to refining and giving precision to the hypothesis that has been formulated, and also *guaranteeing*, i.e., it must be carried out in such a way that the hypotheses of reconstruction can always be *verified*, rejected or validated by all the parties in the case.

Amplifying and **verifiable** are in fact the two founding principles of iterative reasoning, which is made up of the abductive, deductive and inductive phases that

characterize the complex method of scientific thought. The forensic engineer, in other words, must, that is, consider the evidence (the *thing*) with attention and diligence, and, with the assistance of his expertise in the technical—scientific field he should be able to *abduct* (understanding the universal laws) *how* it came about. All this will not be sufficient, however, because he will have to (counter) verify whether his hypothetical reconstruction is really correct. To do that he needs to be able to make abstract deductions about what the consequences would have been in reference to the "laws" that he has identified in the concrete *case* so that he can verify whether his logical deductions, formulated based on his theory of reconstruction, really fit in with all the pieces of evidence from which he started out.

We will clarify this concept later because it is, in fact, the founding principle in the reconstruction of complex accidents. For now, we have understood that the forensic engineer must aim to reconstruct what happened in terms of physical and/or chemical phenomena which have determined the variation of an object from a state previous to the accident to the state which exists subsequent to the incident. Once a hypothesis has been made about the phenomenon or the phenomena that act together and can explain the *thing*, we are now ready to take the next step: *why* did this phenomenon develop, i.e., what provoked it and what were the various different causes.

However, one rule is to be put above all the others: the technical inquiry must be based on pure facts and nothing must be assumed a priori. The inquiry hinges on two founding principles which the criminal departments of the police force are well aware of because they must always be kept in mind during crime scene analysis because of the earliest studies of French criminologist, Edmond Locard[21]:

> The determination of the actions that circumstantiate the commitment of a crime is based on a careful and competent exam of the physical proof that documents the crime scene.

and the second principle, called *Locard's principle of interchange*:

> Contact between two elements will certainly determine an interchange

The two principles set out above must be adapted and applied to the context we are looking at. In our case, there is no criminal who acts and modifies the surrounding environment (crime scene). There is an initial event which evolves into a series of concurrent events (the dynamics of the accident) which leave indelible traces of their development distributed in the form of objects, parts of objects, fractures, signs of reciprocal attrition between components, damage, corrosion, degradation, thermal alteration, etc.

If we compare the reconstruction of the actions of a criminal to the reconstruction of the key events in an accident, it is logical that we should expect that such

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[21] EDMOND LOCARD (1877–1966) better known as the Sherlock Holmes of France. A pioneer of forensic science, in 1910 Locard founded the first scientific police laboratory in Lyon. For further information, see, J. Chisum, *An Introduction to Crime Reconstruction* in B. Turvey, *Criminal Profiling: An Introduction to Behavioral Evidence Analysis,* London Academic Press, London 1999.

events will be reconstructed initially by identifying and interpreting the traces left on the site. However, we commonly hear that people are led to consider the reconstruction of an industrial accident as something that turns out to be much more complex than the reconstruction of a crime scene. It is not possible to make such generalizations, however, except on rare occasions.[22] You need to keep in mind, in fact, that, while criminal acts based on the behavior that is frequently subjective and which can lead to different interpretations, the traces left by a physical system that has deviated from its normal working condition do not obey subjective laws, but well-noted and non-debatable laws of physics and chemistry.

In substance, as regards industrial accidents, the causal interconnection between successive events is based on objective universal laws. The important thing is to use them in the right way, always respecting the first principle: the reconstruction of the dynamics of the event has to "explain themselves" in the traces left on the ground. It must never come about that the traces get subordinated to the hypothesis of reconstruction that is carried out, and they must never be neglected because they are not understood or not easily interpretable.

Based on these methodological premises, the principles that we have set out earlier can now be re-adapted or "updated" based on the technical or scientific progress that has taken place since Locard's day. The main such principles are:

– The determination of the events that circumstantiate the dynamic evolution of an accident are founded on the careful and competent reading and interpretation of all the physical evidence (the traces) that document the scene of the accident.
– If they are correctly interpreted, the traces are evidence of a fact.
– The correct reconstruction of the dynamics of an accident is the result of the logical deductive concatenation of the facts and it is always subordinate to respect for the evidence.

The reconstruction of an accident can always be broken down into a sequence of determining events, which we could define as *key events*, and which represent a substantial modification of the state of the system along the time axis. Seeing as

[22] Think of the objective impossibility of obtaining substantial traces because the dynamic of the accident took place over a large area, or because the area itself is not accessible. This is the situation in the case of the disaster of the Space Shuttle Challenger in 1986, which exploded in flight, scattering pieces over a vast area; or for historical cases nearer to our own times, like the "Ustica Disaster, the Itavia Flight 870" or the "Moby Prince Ship Disaster." As regards the Ustica Disaster many of the pieces of evidence where held in custody at the bottom of the sea until such a time as it was technically possible to salvage them; in the case of the Moby Prince, the fire that caused the death of 140 passengers also cancelled most of the traces that would have been of relevant interest. To tell the whole story, it is interesting to remember that in the case of the Challenger the accident was reconstructed perfectly thanks to the photographic documentation and film footage that the investigators had at their disposal. They were, in fact, able to isolate the moment when the explosion of the spaceship was "triggered." From that photo still, the American physicist, Feynman, a member of the Government Commission of Inquiry, was able to trace the origin of the explosion to the probable breakage of a washer in the bottom segment of the solid fuel rocket.

these key events are in sequence, they must be identified starting from the information available at the scene of the accident and from every other piece of evidence that describes what happened "during" the accident: this can come about, for example, as regards the information registered in a *data recorder* (colloquially still known as a black box), using its elevated number of sensors to take information from the instruments on board an airplane, a ship or an industrial plant. As well as that, each key event that follows (successor) must be causally "connected" with its preceding event (predecessor): if we define, in other words, the key events as "variations of state" to which the system submits with respect to its pre-existing condition, each *successor event* needs to be defined logically, by deducing the evolution of the system starting from the *predecessor event* based on universal laws. Yet, that is not all: the formulation of a hypothesis about the evolution of the system from the predecessor event to its successor must be able to explain all the evidence that has been collected (the traces). To get a better understanding of this concept, we can use a simple diagram as in Fig. 1.1. The diagram shows several sequences of events that can lead in a logical way to the same final event (*top event*) starting off from the same initial episode. What can we do to identify which sequence, from out of the many which are logically possible, is actually *consistent* with the facts? The answer is simply by remembering that we always have to apply the scientific method to "isolate" the *consistent* sequence. The diagram in Fig. 1.1 is in fact an intermediary step in the complex type of reasoning that the forensic engineer is called on to carry out. In any case, having arrived at this point the reader should be able to put the "pieces" together.

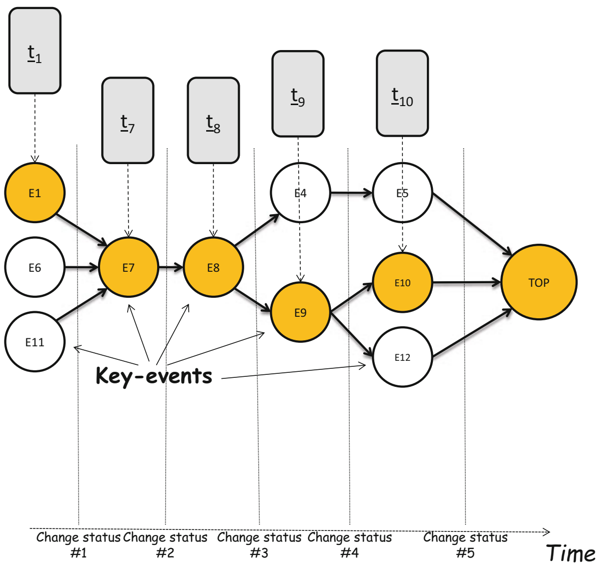

Fig. 1.1 Schematic sequence of possible events of which only one (highlighted in *dark grey*) is to be considered real (*E* events, *t* traces)

Let us see if the *puzzle* has been properly assembled.

The three sequences of hypothetical events in diagram 1 are like the hypotheses of a theory formulated along the lines of *abductive reasoning*, based on certain pieces of evidence such as, for example, some traces scattered over the scene and the registration of data in the black box. The universal laws have been identified by which it is possible to reconstruct the happening, i.e., it is possible, not only to identify the key events of the sequence, but also to connect them causally one to the other, placing them in order, whereby the predecessor comes before the successor. As in diagram of Fig. 1.1 we allow that it has been possible to establish various different sequences of events because, from the evidence we have analyzed, it has been logically possible to formulate a number of key events.

Once again scientific thought as articulated in the three cyclic phases will come to our aid. First, we have to *verify* if the hypotheses that we have formulated about the key event under examination is correct. At the same time, we also have to make sure that, from all the evidence we have at our disposal, each causal "passage" does not turn out to be *falsified* (you can say in Popper's terms) as soon as we try to explain the presence of all the evidence we have collected on the scene, remembering that nothing must be excluded. In other words, we start off from the evidence in the first abductive phase, and then return to the same evidence during the inductive verification phase of the hypothesis we have formulated: we must close the circle, using every piece of evidence.

The *traces* left on the scene are no more than the "effects" of the working out of the particular phenomenon that has allowed the system to "migrate" from one state to another.[23]

To correctly interpret the traces as the *effects* of a particular phenomenon, we need to understand *why* particular effects follow on the evolution of the phenomenon. We therefore conduct an analysis by moving backwards: by analyzing the *traces* the expert is able to extract information that is not generally available to non-specialists. Thanks to the expert's application of specific knowledge he will be able to interpret a particular trace as an "effect" of something, i.e., of the precise phenomenon. Even better, the expert will be able to explain that that type of trace can only be the materialization of the effects of the evolution of a certain type of phenomenon. Starting out from the presence of pieces of tire material on the scene of the accident, the expert elevates the level of information available: by his visual and instrumental analysis of their morphology and chemical characteristics: he can

[23] For example, the traces of braking left on the asphalt and the presence of pieces of tire material found in determinate positions as well as the trajectory the vehicle has taken after the event, allow us, when they are interpreted correctly, to reconstruct the event in question—explosion of a tire. Further analysis, given by the layout of the parts of tire material that we have found at a certain distance from the first traces of braking could amplify our knowledge of the phenomenon: we could infer, for example, that the explosion took place chronologically previous to the use of the car brakes and not vice versa. The explosion of the tire represents the phenomenon which took place in a certain instant of time and which is responsible for the car + driver system in normal driving conditions having passed into a skidding condition with the loss of control of the car.

catalogue the pieces of material, not only as having come from the fabrication of the tire, but also as parts that have been produced as the effect of the tires sudden laceration due to an anomalous degradation.

The interpretation, therefore, proceeds on two levels: first, the expert needs to interpret the trace he has observed to extract as much information as possible; secondly, on the basis of the information he has elaborated, he will have to be able to interpret each trace as the "effect" of something. This second passage requires the expert to know "why" a given effect follows on a given phenomenon, i.e., it requires him to know the causal relations that permit the association of an effect with a phenomenon.

Conclusions

The correct methodological approach to use in the reconstruction of an accident is based on a strict logical examination to which all the hypothetical events must be exposed.

We have to verify that all the hypothetical events obey universal laws in their evolution and that their concatenation is in the same way logically deduced from universal laws that can represent the causal relationship between one event and another: and all this starting off from the presupposition that the reconstruction will have to give a logical explanation for all the evidence that has been gathered.

If any traces in reconstruction activity have not been well explained or if the explanation of reconstruction tends to eliminate, subordinate or neglect one or more of the traces available and certain, we should suspect that the reconstruction might not be true. In such a case, a new logical exam will have to be carried out starting off from the point where the logical sequence got broken.[24]

The methodology to be applied is primarily an iterative process articulated in three distinct phases:

1. the **interpretation of the traces** based on the **universal laws** (*logical abductive phase*);
2. the **formulation of the hypotheses** of the event under universal law (*logical deductive phase*);
3. the **verification of the hypotheses** about the event as a concrete case (*logical inductive phase*).

The correct reconstruction of the facts starts off, therefore, from an exhaustive analysis of all the available traces: in other words, only the correct interpretation of the traces permits us to "fix" a hypothetical event and turn it into a fact. The forensic engineer who uses Sequence of Event Analysis

(continued)

[24] H, Gross, *Criminal Investigations*, Sweet & Maxwell, London 1924.

(or SEA) can provide correct accident reconstruction. On the other hand, practically speaking this is still not enough in criminal trials since it is also required to identify all the profiles of responsibility connected with the facts that have been reconstructed.

This difficulty comes about because of the presence of language "barriers" which impede the technical consultant from talking to members of the legal profession in the correct way. We are not referring here to abstract barriers, but to a precise problem, and these come about whenever the member of the legal profession speaks and thinks in terms of the causal relationship between the **conduct** of the offender and the **damaging event**, while the technical consultant, in trying to reconstruct the happening, talks in terms of the causal relationship between **event** and **event**.

It often happens that these two approaches to "causation" get mixed up, and this has serious repercussions on the correct tracing of responsibility (we will go deeply into this in Chap. 4).

It becomes necessary, therefore, to separate the analysis of the causal **conduct–event** relationship from what is **event–event** on at least two levels of the inquiry. In fact, as we will discover in Chap. 5, there are three levels of this kind plus the basic one (and from this you get the term "multi-level SEA"): the basic level is the one on which the event—event inquiry is carried out (first level SEA), while the other three levels concern the conduct—event relations. This is the theme we will face in the next few chapters.

Chapter 2
An Introduction to Judicial Reasoning in Large Scale Industrial Accidents and Disasters

The Explosion of the Space Shuttle Challenger

On 28 January 1986 the Space Shuttle Challenger took off from the Kennedy Space Center in Florida, but a couple of seconds later it exploded causing the death of all seven members of the crew. It was the most serious disaster in the whole American space program, made even tragic because the launch was followed on a live TV program by millions of people around the world. And yet, until just a few minutes before the launch procedures had all taken place in a normal way and nothing would have made anyone foresee this dramatic epilogue. So, what happened that day in the skies above Florida that was any different from all the other launches that the NASA had carried out before?

The United States Congress asked for an explanation and President Ronald Regan set up a Commission of Inquiry (the Rogers Commission, from the name of its Chairman) to look into the causes of the accident. The investigation was lengthy and they led to the identification of unexpected flaws in the mission's security conditions.

A number of events that would have gone by completely unobserved if the launch had been successful were given relevance in the eyes of the 24 members of the Commission. First, the repeated delays in the mission; the initial program foresaw that the launch was to take place on 22 January 1986 from the Kennedy Space Center in Florida, but it was put off first to the next day and then again to 24 January 1986. Complications had arisen which meant that the sites in Dakar and Casablanca to be used in case of an emergency landing were not completely efficient, and these, in addition to the bad weather conditions forecast over the peninsula of Florida, led to a further postponement until 11:38 hours Tuesday 28 January 1986. In the end everything was considered ready and the control tower gave launching orders, but just 73 seconds later the shuttle, which was travelling at a speed of Mach 1.92 and at an altitude of 14,000 m, was enveloped in the flames of its explosion.

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F. D'Errico, M. Dalla Casa, *The Sequence of Event Analysis in Criminal Trials*,
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Initially both the crew's cabin and the two fuel rockets (the SRBs[1]) resisted intact and the SRBs continued on their separate trajectories. The crew's cabin, on the other hand, continued upwards first because of the thrust, and then, after a short time, began to precipitate at about 207 mph, falling onto the surface of the ocean. After the accident, manned space flights were suspended for two years and only started again on 29 September 1988 with the launch of the Space Shuttle Discovery.

What Went Wrong at Kennedy Space Center

From film footage made available by CNN, who had given the launch live coverage,[2] it was possible to verify that from the precise moment the two SRBs were started up black smoke was coming out of the one on the right, which was where the flames flashed, which later involved the external tank. This footage convinced the experts that the cause of the smoke and then the flames was to be found in the polymeric rings used as holding gaskets for the various different sectors of the SRBs. These rings were called *O-rings* and they were used to seal the gaps between the different assembled sections of the SRBs. To guarantee maximum security a decision had been made to use a system of superabundance and so two of these O-rings had been placed at each juncture so that if the first failed to work the second would have intervened to seal off any possible leaks.

However, as they were made of polymeric material in a rubbery form, in extremely low temperatures the O-rings lost their elasticity.

Unfortunately the unusual period of cold weather that had occurred at the time of the launch, and in particular during the night before, played its part, creating a loss of elasticity so that the second ring could not substitute the failure of the first.

Was this possible loss in the O-rings' holding property in certain weather conditions a risk that the NASA was aware of?

In fact, the problem of their holding properties was something that had been well-known since 1977, to a great extent that Morton Thiokol, the company that produced the O-rings had warned the directors of the launch about the difficulty, suggesting initially yet another postponement. However, NASA's contrary reaction

[1] The two Solid Rocket Boosters (or SRBs) with which the Space Shuttle was equipped where reusable rockets that gave the main thrust to the Shuttle at take-off until an altitude of about 45 km; they were made up of seven segments of steel and were assembled in the Kennedy Space Center in Florida. As far as the Space Shuttle Challenger was concerned the segments were connected together using a circular support closed off with two O-ring gaskets and a special thermo-resistant mastic.

[2] The launch was aired live on TV, even if many viewers followed the repeats aired later in the day. Christa McAuliffe, the first civilian travelling on board a Space Shuttle would have been the first teacher present in a space program and students from all over the world were expecting to follow a lesson given by her directly aired from space.

induced Morton Thiocol's management staff to take up positions that became decreasingly insistent.

Despite the many obstacles that were created, this affair helped to tackle and to reveal the fact that a Space Agency which had designed a vehicle full of defects was also filled with shortcomings in its decision-making processes.

A great number of factors all led to the disastrous epilogue:

– When the Morton Thiocol engineers communicated the weakness of the O-rings in certain operating conditions, the NASA directors considered the risk to be completely negligible, thus making a serious error in evaluation which then led to carrying out the launch in non-secure conditions;
– It was extremely important for NASA not to have delays in pre-established programs because a possible reduction in their funding would have followed. This was one of the reasons why they forced the launching date;
– NASA's activities were inevitably characterized by a high element of risk, and this was the object of continuous confrontations with the different scientific and industrial realities involved in the space program. And yet, the more they mediated the higher the threshold of risk considered negligible was raised;
– The way in which information was communicated in NASA was not adequate to the organizational dimension of the agency or to the internal division of work. A large number of interlocutors were involved in the preparations for a launch but they were in different places, sometimes far away from each other, which meant that it was not possible to create for them profound, capillary and homogeneous understanding of all the phases in the production process;
– NASA operated under conditions of constant pressure from the Congress because of its need for funding, but that had caused hyper-sensibility to the demands of business;
– A defect in design was pinpointed by many people without there having been planned any system that would have permitted the crew to escape in the time between when the descent began and the impact with the ocean surface (about 3 min). Even if this is not certain, it is probable that subsequent to the explosion some members of the crew were still alive and conscious because the emergency reserves of oxygen in their helmets were, in fact, activated (and it is highly improbable that this could have happened by chance or accidently);
– NASA had considered it would be superfluous to introduce ejector seats because they were convinced of the high reliability of the Shuttle; to them it appeared unjustifiable, therefore, to affront the design problems connected with placing such things inside the vehicle.

To explain the causes of the accident, during a press conference Richard Feynman (a member of the Roger Commission, Nobel Prize in Physics in 1965) immersed an O-ring in a glass of cold water, thus giving an empirical demonstration of how its components could lose their elastic properties.

He was so greatly critical of the neglect of security that NASA was imposing on itself that he threatened not to sign the final report if his condemnation was not given in it.

The final results of the work carried out by the Rogers Commission are to be found in concrete form in the following nine recommendations, all of which are oriented towards raising the safety standards of the missions:

– The necessity to redesign the solid rocket boosters (SRBs), after which they would be subject to new structural trials;
– The elaboration of new landing procedures for the Shuttle (even if, in fact, these had no causal relevance in the accident);
– The implementation of new escape procedures for the crew during the initial phases of the flight;
– The creation of an organism to evaluate and reduce risks;
– The re-organization of the Shuttle's launch program to allow NASA personnel on various levels to access information regarding their particular sector of pertinence;
– The revocation and cancellation of all exceptions to the launch requirements in connection with security (for example, there was an enlargement of cases in which the weather conditions would not permit the launch to take place);
– To make public all technical details about the preparation of missions;
– The introduction of periodical meetings during the preparatory phases of the missions so that it would be possible to monitor the state of progress of the work and update the NASA directors on such matters;
– Allow the personnel and the external suppliers to report, even in anonymous form, any doubts or perplexities they might have connected to decision on security.

Despite all these recommendations, 17 years later, on 1 February 2003 a second Space Shuttle, Columbia, disintegrated in the skies over Florida as it was coming down to earth.[3] The crew died on the instant. The Columbia Accident Investigation Board which had been called to investigate the causes of failure in the Space Shuttle Challenger expedition of 2003, bitterly concluded its work stigmatizing the fact that

[3] The Columbia departed from Cape Canaveral on 16 January 2003 on mission STS-107, with the Captain Rick Husband and his crew on board. During the launch, after 82 seconds—as had happened many other times, fortunately without consequences—a piece of the isolating foam covering the external tank came away, hitting at supersonic speed the tiles made of a special type of fire-resistant ceramics to protect the leading edge of the Shuttle's wings. As we have said, it was a thing that happened, and which on other occasions had not created problems. And while Columbia was carrying out its mission attached to the Space Station, despite the fact that many technicians suggested that it would be a good idea to verify the integrity of the tiles, the management of NASA decided not to make any supplementary checks or to intervene. It would have been possible to send another Shuttle in assistance, it would have been possible to try and repair the wing from the outside during a spacewalk. But in the end it was considered "an acceptable risk" or even "of absolutely no concern." On 1 February during descent to earth attrition with a molecule of the atmosphere produced extremely high temperatures. During the changes of direction with which the Shuttle slows down and loses height, the incandescent plasma went through the protection of the damaged tiles on the left-hand wing, penetrated the Columbia, destroyed the structural integrity of the wing and disintegrated the Orbiter.

NASA had not made any significant improvements as a result of the preceding experience in 1986 and that many of the flaws that had led to that failure had reappeared in a partially different form in 2003.

The Explosion in the Nuclear Power Station of Chernobyl

During the 1980s the nuclear power station V.I. Lenin in northern Ukraine (at that time part of the USSR) had become a symbol of the industrial and technological development of the Soviet Union. Its four reactors produced enough electricity for the two million inhabitants of the city of Kiev about 100 km away. It was working in order and was capable of making huge profits.

However, 1986 was a black year for the front line technology of the time. On 26 April 1986 an experiment—defined as a security test—set off the greatest nuclear disaster that history had ever seen until that of Fukushima in 2011. At 1.23 in the morning on that 26 April 1986 reactor number 4 of the Chernobyl nuclear power plant exploded:[4] the core began to melt and tons of radiations leaked out. The environmental consequences of the disaster hit the Ukraine and the whole of Eastern Europe, but the radioactive cloud that leaked from the reactor reached Scandinavia and, although with lower levels of contamination, also Italy, France, the Balkans, Austria and even touched some peripheral areas of North America. The power station continued to burn for ten days and the list of the consequences of that disaster still has to be completed today.

What Went Wrong in the Chernobyl Nuclear Plant

Because of the secrecy covering everything in the Soviet Union in those years, the real causes of the Chernobyl nuclear disaster were still obscure for a long time afterwards and the first real step taken towards a clarification only came about two

[4] Nuclear fission is set off in the reactor of a nuclear power plant. In particular the process of nuclear fission takes place in the core of the reactor. Nuclear fission consists of the decay of the nucleus of a heavy atomic element (e.g., uranium) into smaller fragments, a phenomenon that occurs with a great emission of energy in the form of heat. In fact nuclear fission carries out the same operation in a nuclear power station as the coal in a coal-fuelled power station, i.e., it produces heat. Heat is produced as a result of the thermal exchange between the cooling liquid (water) and the reactor, which is extremely hot because of the fission reaction. This heat is enough to change great quantities of (cooling) water into steam. The steam is then directed towards a turbine, the rotation of which creates electricity according to the principles of an electric generator (electro-magnetic rotor and stator). Inside the core the so-called control rods are placed. These are made of different types of material (e.g., cadmium, silver, etc.) and they are used to control and therefore regulate the entire fission process. Depending on their depth inside the core they can accelerate, slow down or interrupt nuclear fission.

years later after the Post Accident Review Meeting of Vienna. The accident took place at the same time as a test was being carried out to improve safety conditions. The execution of this test had been refused by other power stations because it had been considered too dangerous. Practically speaking, what they wanted to do was to see if during the prolonged shut down phase of reactor number 4 (which needed to undergo maintenance) it would still be able to generate enough power to activate the emergency systems and the pumps so as to circulate cooling liquid at least until the assistance generators were up and working.

The test began at 13:00 hours on 25 April 1986 and the explosion of the reactor took place about 13 hours later. During this time span a great number of factors that are described in what follows all added together and interacted leading to the final result.

This is a summary. The test began by decreasing the power in reactor 4 and this continued constantly for the whole length of the experiment. At 23:00 hours the automatic control system for the cutback of power was disconnected, and from that moment reduction was carried out manually.

However, one of the technical characteristics of the reactor was that it was not stable at low levels of power and every tendency towards its new increase is amplified abruptly that the reactor became difficult to control.

The operators that evening were not aware of these characteristics and they ignored the warning given at about 1.20 in the morning on 26 April by the power station computer immediately to turn off the reactor because of the high levels of risk that had at this point been reached.

But who had responsibility for the management of the test?

The community of scientists that had been called on for the operation was not at all homogeneous, with internal members that were completely different one from the other because some of them had been sent from Moscow to join a group of local experts. These local experts were more conservative and tried to work inside security parameters while the scientists from Moscow wanted to do just the opposite because the possible success of the test would have brought them notoriety, fame and an economic recompense.

Thus it happened that when conflict occurred because the local community were complaining about the violation of procedures and the risks that were being run, the community of scientists from Moscow took control of the situation and forced the local scientists into the back seat. An electrical engineer had been chosen as the leader of the Moscow group—and therefore at the head of the whole experiment. He was not competent in the nuclear field and his career had also been dictated by reasons of political merit. However, even the operators giving him support had only limited or no experience at all in the nuclear area. Further, this the tests were programmed to be carried out during the night when the most expert of the local scientists were no longer at work, but that decision was made based on the fact that the electrical power needs of the city of Kiev would be greatly reduced at night in comparison to its daytime requirements.

As we have said, the test was conducted in low power conditions and therefore when the reactor was seriously unstable. Despite this, the decision was taken to

leave only six control rods in place instead of the usually prescribed 30 (this is a demonstration of a serious underestimation of the danger of the test).

Besides this, it should be added that the control rods had at least two characteristics that should have been kept in mind. First, inserting them into the nucleus was a slow process, which did not go hand in glove with the timing needed to control any possible rapid increase in the core's power when it was working at low energy. Additionally, it was not foreseen that a reactor of that type should be equipped with emergency rods that could be inserted with all speed.

Secondly, the ends of these rods were in graphite. During their insertion this part of the rods substituted the cooling water, thus creating, if only for a few seconds, an increase in the reaction.

Added to all this, there were some other critical points connected with the organization of the plant:

- The roof of the reactor hall had not been constructed in fire-proof material and there was no container building able to resist against the pressure;
- That evening the operators deactivated the reactor's security system even if such an action is forbidden in operating manuals. In this way the core's emergency cooling system was isolated, yet another demonstration of how the risks were constantly underestimated;
- In that situation of instability a decision was taken to activate two extra circulating pumps beyond the six that were already in operation, thus creating an overload in the flow of water.

To sum up, the defects in the design of the power stations were irreversibly amplified during the test and, furthermore, serious errors were made underestimating the risk and violating normal procedures. Added together, all these things led to the dramatic final result.

The Case of Iran Air Flight 655

On 3 July 1988, while the conflict between Iran and Iraq was in full swing the scheduled Iran Air flight 655 (a 300B2-203 Airbus) was flying between Bandar Abbas and Dubai with a flight plan that foresaw the coverage of the tract in only 28 min. As it was flying over the Strait of Hormuz, the airplane was shot down by a missile launched by the US Navy destroyer Vincennes, which was sailing in the waters of the strait.

All of the 290 people on board died during the accident, including 66 children. It is still today one of the most serious disasters in aeronautical history.

The accident was followed by red-hot polemics that involved the two protagonist countries. The United States claimed that the accident had been a mistake, while Iran insisted that it had been a deliberate act of aggression.

The accident was the subject of lively debate in a number of international organizations particularly in front of the Security Council of the United Nations,

where a resolution was approved (n. 616, 1988) in which, after having expressed profound regret for the loss of human life, the need was re-affirmed to put an end to the Iran–Iraq war as had already been expressed in an earlier resolution approved in 1987.

The Iranian government turned instead to the International Court of Justice, and there the two parties reached a settlement in 1996 where the United States Government agreed to pay the sum of about 62 million dollars to the families of the victims, despite not recognizing they had any responsibility in the accident.

What Went Wrong on Board Vincennes

At the moment of the accident the aircraft was in Iranian airspace, and the Vincennes itself, which was coming back from a mission, was sailing inside Iranian territorial waters in the Strait of Hormuz. The destroyer Vincennes was in the area of the accident to act as armed escort to the petrol tankers and the merchant ships that were crossing the strait. In fact, the Iran–Iraq war had been going on for some years, but there had been so many attacks made in 1988 against civilian ships that it was considered necessary to give them adequate protection.

The Vincennes was equipped with the AEGIS system, which permitted the American ships to monitor all that was going on around them by gathering data and re-elaborating it on a series of processors. This was, in other words, a combat system that integrated sensors, instruments of war and mission equipment. The crew of the Vincennes thought that they were about to come under attack and made the mistake of interpreting the Airbus 300's trajectory as descendant, i.e., something that would be typical of an airplane in attacking phase, rather than ascendant, which was the airplane's true path.

All this happened despite the fact that the AEGIS system had correctly read and transmitted the data it had picked up. Once you have recognized the mistake made by the crew, what can be said about the various different causes that determined such a macroscopic oversight? If we think about this on the abstract plane, would the substitution of the crew which had made such a mistake with another be able to completely eliminate the repetition of such an accident?

The AEGIS system, whose most evolved versions are still in use on American Navy ships was created with a war scenario in mind, that is to say a situation inside which the distinction between friend and enemy was truly clear.

Yet the situation in which the Vincennes found itself did not have such unequivocal connotations. They were inside a war scenario, in which, however, everyday life was going on as normal. There was a continuous overlapping between war and civil scenarios and in some cases the difference between the two became a little indistinct.

An important contribution towards the correct overview of the various causes of the disaster came out during the course of a documentary made in 2000 by National Geographic Channel. During the program the American Government prospected a

different reading of what had taken place. The hypothesis was made that the crew had been subject to a particular phenomenon called "scenario fulfillment."

Here we are talking about a special psychological condition that hits a group of people trained to face a particular situation: the training received predisposes the subjects of the group to identify the existence of a situation for which they have been prepared even if it does not really exist.

This can happen even if the data of which they are in possession is correct, because the operators are inevitably influenced by the tensions they are undergoing.

The possible sources of mistakes can, therefore, have deeper and, at first sight, totally unexpected roots.

The Causes of Failure: The Thread Connecting Large-Scale Accidents and Industrial Disasters

All the examples we have given are symptomatic of an incontestable fact: an error has multiple origins leading back to human and technological factors which are localized at a distance in both time and place from the moment and the site where the final event occurred.

But why do we speak about an error? It seems evident that the subject we are looking at is connected with non-voluntary conduct which is not, therefore, intentionally directed towards provoking a disaster, an accident or a tragedy.

All this is totally different, for evident ontological reasons from cases in which someone acts with the willful scientific aim of triggering a disaster.

However, involuntary conduct would be unlikely by itself to generate such a dramatic outcome if it were not for the fact that it is inserted into a system that is itself complex, and contains internal flaws, which, in connection with such conduct, set the events moving towards their final solution.

It is easy to understand and demonstrate, therefore, how the causes of similar tragedies are to searched out in multiple human and technological factors, in such a way that solutions from one of them alone are neither enough nor adequate, in particular if the logic of your actions is to verify and eliminate the conditions that have activated those mechanisms that caused the disaster.

From this point of view we must recognize that a reconstruction of the causes leading to industrial disasters (so defined because they involve man's productive activities, like, a transport system) can have a double purpose—on the one hand to outline responsibilities in a legal framework, with methods of inspection subject to verification according to the rules set up in each single nation's juridical system; on the other hand, analysis of this type are an area of study for experts in the sociology of organizations and the failure of complex systems.

Any coincidence between these two relevant spheres is only apparent, in that there is no total overlapping of the two types of analysis. Not everything that is important from the point of view of the sociology of organizations can necessarily

take on relevance in the field of judicial responsibility, in that this last will be affirmed or denied on the basis the verification criteria that are peculiar to each system.

For this reason, we should make things as clear as possible right from the beginning.

One of the most important effects of industrial accidents is the loss of confidence; if an organization fails people tend to lose their trust in that organized system and this in turn creates new costs of credibility, trust in the system and in the use made of the system.

The will and the ability that a system demonstrates in correcting itself are, therefore, fundamental components of its reliability; in as far as the system is able to revise itself and rectify its flaws, it elevates its level of efficiency and the trust in it shown by its users and operators will tend to grow.

Little or no will or ability shown in correcting its mistakes or defects lead to a loss of trust in the organization and an underestimation of its reliability and therefore of the services it offers, with heavy consequent falls in economic and human terms (a drop in the company's activities brought about by the little conviction shown by its users have direct effects on employment levels).

But that is not all. Even if the organization is able to rectify its mistakes, the fact remains that a reliable system cannot fail to penalize the conduct of those who, maybe even violating the law or work instructions that have been laid out, have contributed to causing the final event.

Here we are not talking about applying the letter of the law, this is no accusatory vision, but only an objective fact: the principle of the responsibility that results from flawed conduct is a cardinal tenet in every system (whether it be social or industrial) in the absence of which the structure itself is destined to create an opposing culture—based on the absence of such responsibility—which will, on the one hand continue to cause accidents because it tends to push the weaker operator's competence and diligence down to lower levels, and, on the other, will demotivate the best of them because they will not feel adequately considered. Clearly the mechanisms used to sanction can be of various types; they can be built into the system (internal disciplinary procedures), external (penal sanctions if a crime has been committed) or, generally they can require the payment of damages (you can indemnify the injury that has been provoked to an organization or to extraneous persons who have suffered loss or harm), but in any case they must be correctly proportionate to the seriousness of the conduct that has contributed to the onset of the event.

It is generally reasonable to claim that an evaluation of the significance of errors in conduct can be identified based on two factors. The first is established by the extent to which the diligent conduct that you could legitimately expect from the operator diverges from his or her real behavior in the case. The second is given by the extent of the real consequences that derive such conduct. Damage to things can have a certain value, but damage to human beings in terms of death or grievous bodily harm quite necessarily can have another.

There might not have been any particular consequences (e.g., the derailment of an empty carriage, part of a goods train which causes no damage either to persons or infrastructures), but even then it is still useful to make evaluations to avoid the repetition of similar occurrences which could have an even drastic outcome.

Further, the extent of the damage provoked can depend on many different circumstantial or merely causal factors, and for this reason many people claim that it is the fact itself that deserves particular evaluation and that it is not only the extent of the consequences that makes it necessary to devote special studies to such accidents. If anything, the more the conduct actually carried out is at variance from the conduct that should dutifully have been held to, the greater the reproach moved against the operator and therefore the heavier the possible sanction that will be applied.

However, not all the types of conduct that we have seen now have criminal relevance; they are not all crimes which can be followed by a reaction on the part of the state that could have an effect on an individual's personal liberty. The fact that you have projected a nuclear power station (Chernobyl) that becomes unstable at low energy levels is not in itself reprehensible, but it becomes so if such characteristics were unknown to whoever was on the point of carrying out a high-risk test which presumed that the operator in question was in the possession of precise in-depth knowledge about the plant he or she was about to be working on.

Quite obviously, every legal system has its own characteristics and each of them is the result of a juridical culture that has been created, has evolved and been formed over long years. The difference that exists between the different systems, however, cannot stop us from making observations that, generic as they may be, still allow us to delineate a framework inside which we can claim there to be criminal responsibility.

We have spoken about an error as the cause of a disaster-event and we have seen how this is involuntary behavior with respect to the final result. None of the operators in Chernobyl wished to provoke the explosion of the reactor, just as none of the workers or directors in NASA who were involved in the 1986 launch wished for the mission to fail. Yet, errors were made: in evaluation, planning and execution. These were certainly not sought after and were not given concrete form in any *active* ('I did something I should not have done') or *omissive* ('I did not do what I should have done') conduct.

In both cases we must remember that the sources of error are constantly in movement. Improved science or deeper knowledge will enhance our understanding of the consequences that can derive from behavior whose implications we knew nothing about in the past. In the same way, the greater complexity of a system can widen the margins of error, and an overload of information can also lead an operator into error if it is not managed well and if it exceeds his or her work load capacity.

What both these hypotheses (active and omissive conduct) have in common is the negligence that brings them about, which, in its turn can take on many aspects like people who:

- Omit, because of their inadequate care, to carry out a duty connected with their work (e.g., the nurse who forgets to give a patient his/her medicine thus provoking an illness or even death);
- Do not acquire the necessary knowledge needed to evaluate the consequences of what they are doing even when such expertise is strictly connected to their function and is therefore part and parcel of their work (e.g., the fact that those who were given the job of directing the test in Chernobyl did not know about the characteristics of that particular nuclear power station);
- Even though they are in possession of the necessary know-how, still make mistakes in evaluating the consequences that derive from their conduct or the situations that they are facing, thus taking the wrong decisions (e.g., the fact of having proceeded with the test at Chernobyl despite the state of high risk in which the nuclear power station was functioning at that moment).

The fact is that, more often than not, we tend to convince ourselves that the mistake made by the last of the workman is the only cause of an accident. In this way we are led into accepting this as the simplest and most reassuring of explanations. This is a matter that we will deal with in Chap. 5, but it is worth underlining even at this early that, by accepting the most banal of explanations, we are destined to perpetuate the risks and will not in this way eliminate the causes of the mistakes that lead to industrial accidents.

Introduction to General Principles of Causal Relationship in Criminal Law

The first thing to "trace" the responsibility of a subject in the criminal sphere is to understand whether the (de facto or juridical) situation can be seen as a crime. We have to verify, in other words, whether the situation that has been created is of an anti-juridical nature, that it is blameworthy and that it can be punished. Juridical analysis of a crime shall clearly underline a series of objective elements placed one after the other. Practically speaking, it is made up of all those objective elements that contribute to the description of a form of offense, which is to say:

- **conduct**, i.e., an action or an omission;
- the **prerequisites** of that conduct;
- the **event** (or events), that is the occurrences separated in time and space from that conduct and caused by it;
- the **causal relationship** between the conduct and the event;
- the material object, i.e., the person or the thing on which the **action**, the **omission**, or the **event** has a bearing;
- the juridical or de facto **qualities and relations** required on the part of the active subject of the crime in so called job-specific crimes, that is, crimes that can only

be committed by a person who holds a particular position or has a particular qualification;
- the **offense against a juridical good** protected by the incriminating norms, in the form of damage or danger.

Event and **conduct** are two distinct entities in criminal law, but they are not autonomous: there must be a link between them, or, to be exact, a **causal relationship**, without which the external occurrence could not be considered an effect of the offender's behavior. The **event** is an element which is "outside" **conduct**, but connected to it by a specific causal relationship which exists when the first is an effect of the second.

We have already defined **conduct**, on the other hand, as the behavior of a person, which can have a double content, we remind, it can be either *active* when it consists in doing something which brings about the detrimental event, or *passive* when it consists in not doing what would have impeded the occurrence of the event itself.

Both of these are anti-juridical in the same way once the foreseen event caused by them has come about, and criminal sanctions are applicable to each of them. We could therefore say that the **causal relationship** (or connection) is a sort of natural link (i.e., one that is dependent on a physical phenomenon) between the (offender's) conduct and the damaging event incriminated by the law.

This is the fundamental relationship from which the judge will—once the facts of the crime have been reconstructed—decide whether to impute a particular subject with the crime itself. It follows that it thus becomes vitally important for the judge to understand how it is possible to state that such and such an event is truly an effect of such and such a conduct. Seeing as this causal relationship itself—or rather the correct interpretation and weight that needs to be conferred upon it in tracing profiles of responsibility in accidents involving systems or complex organizations—is central to the discussion that is developed in what follows, we must first outline the various theories of causation in the juridical sphere, referring the reader to specialized texts on the subject of criminal law for all further details.

To verify that this causal relationship between an action (human conduct) and an event effectively exists you carry out the so-called *but-for test*: an action can be called the cause of an event when it is logically demonstrable that if you hypothetically eliminate it from the series of actions preceding the event, this itself would not have occurred.[5] On the other hand, when we turn this reasoning back to front,

[5] The main criticism raised against the but-for theory concentrated on the fact that it can take on precise characteristics only in cases where we are already aware of the causal laws that govern certain occurrences: in the absence of such a scientific law—or because of the blank in our knowledge of it—this theory continues to be an empty formula which cannot explain the reasons behind an event, for as long as, at least, scientific knowledge is unable to resolve the specific set of problems. A second criticism moved against the but-for theory concentrates on the fact that, if taken to extreme consequences, its application leads to the idea that preceding actions farthest in time from the event can turn out be considered conditions of occurrence itself (i.e., the sale of a gun to the killer in relation to the death of a man because of the gun sold to the murderer). Lastly, the following has been a third element of reflection: what would happen if we were faced by two or

human conduct cannot be considered the cause of the event in circumstances where, even after mentally eliminating such conduct, we can see that the event would have come about all the same. The common problem for lawyers consists in how to explain and demonstrate what the specific causal relationship really is, which determines a destructive event. This means, in other words, that we need to reconstruct—starting from the damaging event and moving backwards—the consecutive chain of antecedents which, on the basis of regular succession and in conformity with a scientifically valid law leads to [damaging] events like those which have come about in the concrete event itself. As we talk about scientific laws, we are talking about universal laws which allow us to verify if a specific event can really be considered antecedent to the occurrence of another "subsequent" event.[6]

Conclusions

Juridical doctrine in various national law systems has elaborated numerous theories relative to finding the causes that have led to the occurrence of the damage in question. Not all the conditions or the behavioral antecedents preceding the event can be considered as causal links between the conduct and the crime, but only those without the existence of which the crime would not have taken place. The principle of the equivalence of causes in any system, based on the identification of the causal connection between conduct and event, hinges on the paradigm offered by the but/for theory or the theory of the *conditio sine qua non*.

On the other hand, the theory of the *conditio sine qua non* (i.e. the but-for-test) qualifies the instruments necessary to the identification of the cause or combination of causes. It assumes that we must consider as a condition of the

(continued)

more examples of conduct which are independent one of the other, but each sufficient to cause the event? In such cases, we would be forced to conclude that neither of them is to be considered the cause of the event in that the (abstract) elimination of one or more would lead us to conclude that the event would have occurred in any case. To clarify this last concept, let us have a better look at an example: unaware of the existence one of the other and both acting independently, individual A and individual B shoot at the same subject's head and he dies. Eliminating A's (or B's) conduct we would arrive to the conclusion that the death event would have taken place in any case. It follows that A's (or B's) conduct cannot be considered the cause of the event.

[6] Statistical laws are also to be considered covering laws when they allow us to state that the occurrence of an event is destined to be followed in a particular percentage of cases by the occurrence of another event. In reference to statistical laws, the higher the probability is that the occurrence will take place, the greater the validity of the statistical law referred to. As regards all this, we refer readers to Chap. 3 for a discussion about the validity in probability theory of a "statistical law," a concept which, to tell the truth, is applied in a fairly confused way in certain areas outside its specific medical examiner sphere. For now, we will limit ourselves to following these arguments in a state of the art juridical field. We need to clarify, first, that a "statistical law" (or, as we should say correctly "relation" rather than "law") must never be exempt from undergoing an "added verification" in order that its logical probability can be "weighed" so to speak, i.e., its degree of rational credibility.

event only that which is necessary and sufficient to the occurrence of the damage or the lesions. The crucial problem, rather, to which a reply must be found, is this: what is necessary to be able to claim that a given event is the consequence of a given action.

We have to establish in a concrete way what we mean when we say that we are interested in identifying the combination of causes of a damaging event. This is particularly important in those cases where the event is articulated in its turn in a causal sequence of accidental events (in the sense where one accidental event is always an antecedent of another) and this sequence can be figured as the consequence of many different causal factors.

We are asking ourselves, in other words, how to approach our task when we have to identify the liability of a subject (negligent or intentional as that may be) in the case of a complicated industrial accidents, which are usually made up of various different events organized in a consequential or chronological system. In the following chapters we will try to find an answer to that very question.

Chapter 3
Causation by Scientific Laws

Introduction

A relationship or a scientific law describes the regular sequence of a happening obtained by the result of the systematic observation of physical reality which is therefore characterized by the repeatability of its results being equal the recreation of its initial conditions. This aspect has been heavily underlined in Chap. 1. We have said that in its very nature the scientific method consists of repetitive logical phases (the abduction phase, the deduction phase and the induction phase, cf. - Chap. 1). These three phases enable us to formulate a hypothesis which can explain the observations we have made, to foresee from these same hypotheses a number of "states" of evolution in the physical system under consideration and validate the consistency of the hypotheses formulated using a further phase of verification.[1]

In Chap. 2 we gleaned the basics of a counterfactual analysis, such a reasoning that allow us to verify whether a direct causal connection between a particular conduct and an event exists. Practically speaking, we are induced by the but-for test to mentally eliminate the specific action or non-action of the subject, and by this way we can deductively verify if such particular damaging event would not have taken place. Now, what we are doing by this way is to check the causal relationship that could exist between an act A and an event B. If the event B and the conduct A

[1] Frequently, we are talking about verifications carried out by experimentation, sometimes of demonstrations from logical deductions. In this sense, we could refer, for example, to the deductions formulated by Einstein in creating his Relativity Theory, which consisted in long mathematical demonstrations, i.e., by developing complex mathematical equations. Paradoxically, Einstein reached the definition of his theory of relativity without ever carrying out a single experiment to validate his thought, but using only reason and mathematics. Other physicists, contemporaries of his, would have the burden of using experimental methods to verify the consistency of his theories. This is a rare case in the history of scientific thought, in which a scientist discovered a law that was universally valid without ever knuckling down to the phase of experimental verification.

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are clearly and directly related, the but-for-test would be sufficient by itself. But, there is a "but" in everything: how should we behave in a case where the damaging event comes into being at the end of a long chain of accidental events[2]? Could we say, for example, that if conduct A is the cause of event B it is also responsible for an event C which seems to have been sparked off casually by event B?

This for us is a central question because it is precisely to find an answer to this question that authors have worked out on multilevel analysis by the Sequence of Events. Let us proceed step by step.

We have to first define the **causal relationship** between an action A and an event B through identifying the scientific law (or laws) relevant to the specific case we are dealing with. Specifically, the procedure that we apply consists in a deductive syllogism from a major premise and a minor premise, as it follows:

- A major premise shall be stated by defining which are the universal principles or laws that describe the regular succession between the class of occurrences A and the class of occurrences B. For example, there is a regular relation between occurrence A, "injury to the cardiac muscle" and occurrence B, "death"; in logic this is written "if A, then B" (or, as expressed in Boolean logic, $A \rightarrow B$);
- A minor premise shall be stated clearly including a concrete event that is "covered" by that universal principles or laws above defined. For example, the human action *a* "firing a pistol shot at a man's heart" was followed by event A, "injury to the cardiac muscle; in logic this becomes," "if *a,* then A" (or, as expressed in Boolean logic, $a \rightarrow A$);
- The conclusion shall be point out by a syllogism about the effect on damaging event produced by action which has been concretely carried out. For example, the human action (namely the conduct) *a* "firing a pistol shot at a man's heart" is the cause of the concrete event B "death of a man", and, in logic, this is written: "if *a* then B", or, once again applying the simple rules of Boolean logic $a \rightarrow A \rightarrow B$, which is the same thing as saying $a \rightarrow B$. The concrete case B "death of a man" is therefore the result of the concrete action *a* "firing a pistol shot at a man's heart" because the connection between the conduct *a* and the damaging event B is guaranteed based on a scientific principle.

It is worth of noticing that here above we are dealing with deductive syllogism that is not fallible only in case the premises it starts from are in fact true. In the example we have rough out just above the concrete action of "firing a pistol shot" is connected with the damaging event "death of the man" based on the causal relation deduced by the medical pathologist.[3] Pathologist could be able to testify that, in the presence of such an injury to the heart, the result will certainly be death.

[2] Cf. the diagram in Fig. 1.1, Chap. 1.

[3] To allow for simplicity of discussion we can leave out the fact that in this specific case the non-specialized knowledge of the man in the street would be enough. Let us imagine, however, a situation where there is real need of an expert's specialization. In any case, even in the complexity of the disciplines that are being utilized, knowledge must be transferred and made comprehensible to the non-technician, such as the attorney, the judge, the magistrate.

Furthermore, to formulate the minor premise, the medical pathologist infers in this case from the available evidence that the injury to the cardiac muscle has not been produced by an unknown cause—an illness with which the man was affected or any other strange phenomenon—but originated in the bullet that was fired. The injury to the cardiac muscle that provoked the death is, therefore, connected with the firing of the pistol shot, which is with the conduct of the person guilty of having carried out first degree murder.

Akin to a crime of gun shooting a man, in cases involving industrial accidents the phenomena which develop obey the laws of physics and chemistry. The difficulty in reconstructing an accident is not so much because of the fact that we have to identify the "laws" that "connect" two succeeding *key events* (cf. Chap. 1), but to the fact that we are obliged to use an *ex-post* analysis to identify all the *key events* of the accident. All the *key events* that have been found need to fit together to determine a sequence that is at the same time *coherent* (namely a sequence of events that is logically possible) and *consistent*, that is such a particular sequence which, amongst all the *coherent* sequences, is the just one capable to explain all the available traces. Depending on the complexity of the causal "relationships" that we have examined, we can always utilize logical deductive reasoning based on fundamental, universal laws, like the laws of ballistics to determine the trajectory of a bullet starting out from the trace it has left when finishing up in the wall. We can try, in other words, to apply the laws of the motion of projectiles to discover the probable point from which the shot was fired. And then, in a second reconstruction, established that we have demonstrated that a second shot fired from the same gun hit the heart of a man and killed him, we can call in the medical pathologist as in the previous case to unequivocally demonstrate whether the death of the man was caused by the shot that has been fired. It is not necessary—because of high "quality" of the information gathered—to fall back on "statistical laws" used to search for some correlation that would establish the probability of a man's death caused by a bullet having perforated the cardiac muscle. Neither would a ballistics technician dream of proposing the setting up of a "shooting trial" with a gun that is compatible with the one that has fired the shot, varying the shooting positions taken up by the gunman, and examining the results of these experiments to determine the probability of lodging a bullet in the same position where the one being used as evidence was found.

This approach, which only looks paradoxical because the case is totally simple, gives rise to heated debates in court rooms and is unfortunately often used as a sort of heal-all that can reconstruct a fact. It is a serious mistake to assimilate a fact with an experimental *test* that is only hypothetically well-constructed. Every test is affected by a 1000 unknown variables: the gun is similar, but it is not the same; the firing positions are analogous but they are not exactly those of the original; the person firing is a professional with good shooting technique, but he does not have the ability of the murderer. Does the gun have the exact same firing power even if you use a gun of the same make or model? Was there a side wind at the moment the gun was fired?

Just because you have carried out an experimental trial, it does not mean that the *test* performed was completed in agreement with the scientific method: it would be better rather to speak about this as a *technological test* rather than a *scientific test*.

Let us try to understand the difference by elaborating on our simple example. Consider two different approaches that have been followed by two ballistics technicians and who are being listened to about the possible reconstruction of the bullet's trajectory. The trajectory has taken on relevant importance for the judge because it would permit him to begin to identify the zone from which the bullet was fired.

The first technician has made a competent examination of the case with the help of the laws of ballistics (deduced from universal laws, i.e., the laws in physics governing the dynamics of a body that is moving in a gravitational field). He concludes that:

> It is reasonable to suppose that the gunshot went in a precise trajectory reconstructed from the three exact measurements of an angle of a straight line (represented by the trajectory of the bullet) in space. These angles have been measured based on the hole (the 'trace') left by the bullet when it lodged itself in the wall. From the absolute angles in space it is possible to trace back a trajectory that most probably leads to X floor, building Y.

The second ballistics expert, instead, illustrates the results of a "technological shooting trial" that he has set up: from different positions a professional marksman aims at a point that represents the area of the wall where the bullet has been found lodged. Interrogated then on the results he has obtained, the second technician concludes that out of 100 attempts, 2 shots were lodged in positions near to the original location and the others were not (all this in the hope of having used plausibly similar shooting parameters!). The paradox tells us that the probability is extremely low that the gun was fired from position X in building Y (2 %). It follows, therefore, even if the occupant of apartment X has no alibi for that given day and that given hour (and even has, perhaps, a possible motive), the low probability of the result obtained, calculated based on these shooting trials, suggests that we should look elsewhere for the culprit.

This example goes to show that a scientific reconstruction presupposes the use of universal laws or relations that have been deduced using scientific methods that are generally compendious than the various disciplines where technical consultants consider themselves experts.

You use technological trials only when: (a) you are sure that you have all the parameters of the trial under control, or if (b) you are conscious that you are acting in a non-scientific but empirical field with all the advantages and disadvantages of this special case. The disadvantage is certainly connected to the fact that a technological trial can never rise to the heights of a scientific law: if the hypothesis that you want to demonstrate is not confirmed by the trial, it doesn't mean that what you have formulated is false. It could also mean that the surrounding conditions and/or the parameters you have used in the trial were not consistent with the original ones. The advantage, on the other hand, derives from the fact that if the technological trial is well organized and the result you wish to obtain is circumscribed it can manage to

demonstrate a hypothesis although in a simplified form (and sometimes even have a strong "effect" in a Court). Consider the case of a shooting test set up with a firearm. To validate whether it really is the gun that fired the shot extracted from the body of the victim; no universal law is involved, but a simple empirical comparison between the observable marks on the bullet from the body and those consequent to the gun fired in the test is an affective evidence.

Causal Relationship and an Accidental Sequence of Events

Now it is time to finish off our analysis of some aspects of the *but/for theory*, in particular those regarding sequences where you have accidental events. We need to start to gain confidence when the causes as determined are necessary and sufficient to determine the damaging event or, alternatively, accidental events have interrupted the causality chain become themselves causes of final damaging event. For example, returning to gun shooting a man:

a) A causal relationship between conduct of firing man and death of the man who has been shot cannot be excluded if the death of a person victim of a superficial firearm wound is caused by his/her particular vulnerability because of hemophilia;
b) The causal relationship is not excluded even if a further causal factor, other than the original crime, consists in an illicit act carried out by a third party, as comes about in a case where man wounded by gunshot needs a surgery because his life is in danger, but then dies during an surgery operation that was considered necessary because of a certain *probability* the patient would survive, but it was not successful because of a mistake on the surgeon's part.

   Instead, the causal relationship is excluded when between the action and the event an autonomous causal series inserts itself, i.e., a causal series that is by itself sufficient to cause the event: in such a case, the action is only a temporal antecedent and not a *condition sine qua non* of the event.

   Thus in the previous example:
c) If the gunshot victim has a wound in his leg that is not, reasonably speaking, considered serious because it is superficial, and he is left in the waiting room because there are emergencies in course, but then the waiting room is involved in a fire which determines the death because of serious burns of the man, the person who fired the shot cannot be considered guilty of the death of the man; he cannot, that is, be charged with murder but only, possibly (depending on this being demonstrated during the hearings), with attempted murder, rather than grievous bodily harm. The death of the man has, in fact, been caused by other factors having come about which exclude the causal relationship between "the breaking of superficial skin tissue" because of the bullet and the event "death of the man," in that this is uncontrovertibly attributable to the consequence of serious burns covering more than 50 % of his body.

It might be useful to dwell for a moment on an apparent contradiction incidental to the examples given in cases a) and c) above, which certainly did not escape a reader who has experience of the reasoning behind how to gather evidence.

Case a) is an attempt to recreate the conditions enabling us to state that whoever fired the gun should be considered responsible for the death of the man, even if he did not “aim” at a vital organ, but, for example, at a leg: more so when a gun wound to a leg involves tissue that really is superficial. In the majority of cases, this means that when the injury undergoes suitable treatment (and if that does not happen, we would then be talking about case b), a fire gun wound of this type should not lead to the death of the victim.

In most cases, that is to say: but in the concrete situation under examination, you cannot be sure seeing as we are in the presence of anomalous and rare conditions not normally to be found.

Even if we admit that the person who fires the gun cannot be conscious of the other man’s particular pathology, there is still a causal connection between the action “firing a pistol” and the event “bleeding” which in this specific case becomes the reason for the death through “loss of blood” because of the victim’s hemophilia.

Not being conscious of the victim’s particular pathology and not having aimed to kill become subjects of debate, during which it has to be demonstrated whether the crime committed was in fact grievous bodily harm, manslaughter or even homicide, if and when the aggressor’s knowledge of the victim’s rare pathology could be proven.

In conclusion, the external factor in the man’s conduct represented by the rare pathology of hemophilia cannot be interpreted in this concrete case as a feature able to establish an “autonomous causal sequence” as holds true instead for c); the pathology of hemophilia is itself the causal link between the copious loss of blood and the death, and this loss of blood is to be reconnected—once again moving backwards—to the superficial gunshot wound.

What we have set out in c) is totally different because in this concrete case the man’s death is provoked by the serious burns undergone during the fire (i.e., the sudden appearance of a separate cause), which has nothing to do with the injury caused by the gun shot; more so that the personnel in the Emergency Department did not consider the man’s life to be in danger when he arrived at the hospital.

The Concrete Case Under Universal Laws

There are a great number of theories about the causal connection between two events separated in time. In certain contexts it can be plausible to build up a chain of events pertinent to the “historical” interest in that particular sequence of episodes rather than in any “theoretical” causal explanation for what occurred.

To clarify, let us look at an example taken from Norwood Russell Hanson (1924–1967):

> Suppose that Galileo's carriage strikes a pedestrian in the darkened streets of Padua. The coroner might consider the circumstances: if only that banana skin had not been on the kerb; if only the driver had not been glancing back; if only the rivets I the brakeblocks had been secure. He too might set out his report: for want of a rivet a brakeblock was lost, for want of a brakeblock the distracted driver could not stop in time, for want of this control the carriage struck the Paduan who had slipped into the street because of the banana skin; this resulted in death-all for want of a rivet.[4]

In his example of the carriage, Hanson demonstrates what we commonly understand by a linear sequence of events, i.e., a concatenation of events in a space time order inside which an "ascendant" (or predecessor) anticipates, again from the space time point of view, a descendant (or successor).

Scientific inquiries, however, rarely proceed in an ordered way, moving towards the discovery, that is, of a "chain of cause and effects." In fact, Hanson underlines the fact that treatises and texts of physics have in the last 300 years contained elements of scientific inquiry that are "less like the rings of a chain and more similar to the legs of a table."[5]

Given their casual nature, we call the sequence of events in their space time order *accidental sequences*.

Now it is true that we commonly consider and interpret a preceding event as the "cause" of the subsequent event. It would be natural to think of the defective rivet as the cause of the fact that the brake plate did not work, which did not allow the driver to stop in time.

In other words, a reading made of the events set out in a linear sequence created to determine their cause would lead to the probable conclusion that, if the rivet had been correctly fixed in its place the man would not have been run down. It would be enough, therefore, to move back step by step through the accidental sequence of events to identify the "first cause" in the absence of which nothing would have taken place. And yet, unfortunately, that is not sufficient: i.e., it is not enough to know how certain facts are set out in temporal order. That is why in speaking of such things Hanson concludes:

> To understand how the Paduan pedestrian came to grief, it is not enough to know that certain incidents were strung out in temporal order. . .One must know what usually happens when people step on banana skins, when drivers are distracted at dusk, when the rivets on brakeblocks are insecure. The primary reason for referring to the cause of x is to explain x. There are as many causes of x as there are explanations of x. Consider how the cause of the death Consider how the cause of the death might have been set out by a physician as 'multiple hemorrhage', by a barrister as 'negligence on the part of the driver', by a carriage-builder as 'a defect in the brakeblock construction', by a civic planner as "the presence of

[4] N.R. Hanson, Pattern of Discovery, Cambridge University Press, London, 1958.

[5] To put it in Hanson's words "to know why the kingdom was lost it is not enough to know that a battle was fought, that a battalion and a rider fared badly, that a horseshoe-nail was missing. It is also necessary to be familiar with the frictional properties of nails imbedded in cartilaginous substances, to know why horses are happier when shod, why dispatch carriers requires horses, how helpless an isolated battalion can be, how much an army's fortunes can depend on one battalion, and the ways in which the security of kingdoms can depend on military success."

> tall shrubbery at that turning" [. . .] 'Effect' and 'cause', far from designating the rings in a chain of events, show theoretical knowledge, information and models of experiments, closely interconnected. [. . .] Causes certainly are connected with effects; but this is because our theories connect them, not because the world is held together by cosmic glue.[6]

Identifying the first cause of the final event essentially through a temporal reconstruction of such events would be like saying that the prime cause of the Great War was the homicidal conduct of the Sarajevo assassin against the Archduke Franz Ferdinand of Austria, heir presumptive to the Austro-Hungarian throne. It could be an incontrovertible fact that a series of interconnected descendant events took place subsequent to this episode which led to the First World War, but it is equally true that it would horrify any historian if we were to deduce from this that the Sarajevo assassin was the cause of its outbreak.

Let us have a look at another example.

Consider a man who has been wounded in the leg by a gunshot fired by another man; the first man subsequently dies as the consequence of a serious road accident involving the ambulance that is taking him to hospital.

In connection with what has been said so far, we try to move back through the sequence of events to identify the so called "first cause," the one from which, so we believe, all the others originate. In a counterfactual way, we could reason as follows: if the first man with the pistol had not shot at and wounded the second, then this man would not have been in the ambulance at the moment of the accident and would not, therefore, have died.

The important question to face up to concerns the inherent error contained in the reasoning behind collecting evidence that has been structured in such a way: looking for the cause and effect connection between the conduct of an offender and the event by basing everything only on the concatenation of the events.

Instead the reconstruction of the concatenation of events is only the first act in the complex search for the associated causes that that have made the system evolve from its initial observed state (first event) to its final state (final event or *top event*). The expression *first cause* is, therefore, all too often abused, confusing the meaning of *cause* with that of *event*. We should often, that is to say, speak about a *first event* rather than a *first cause*. The *first event* is the point in time from which we could reasonably start our analysis of the concatenation of events: this is the event during which the system began to show substantial, observable and measurable signs of changing away from its usual functioning mode.

Let us clarify this last consideration with another example.

A car is traveling within the speed limit along a lane of the freeway. Because one of its tires has a blowout the driver loses control and crashes into the guardrail. The fact that the airbag does not deploy leads to lethal consequences for the driver.

What is the cause of the lethal accident? Who should be considered responsible for the death of the driver?

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[6] N.R. Hanson, op. cit.

Thinking along the lines set out above from the reconstruction of events there introduced, we have:

blowout of the tire → the car swerving out of the freeway lane → crashing into the barrier → lesions → death of the driver

We conclude that everything has its origin in the blowout of the tire.

If we apply a counterfactual reasoning we would still deduce that the "blowout" is the event in the absence of which the driver's death would not have come about. In other words, we could conclude that the blowout is the *prime cause* of the driver's death because it is the *condition sine qua non* of his demise.

The subsequent inquiries, therefore, would be directed towards understanding whether there was an original defect in the fabrication of the tire, or if maintenance had been badly carried out in time or whether the *causes* are to be looked for in the residues of material scattered along the road, which might be able to account for the blowout. No attention is given to the fact that a tire blowout, even if it is a serious and dangerous event, is not in itself enough to determine the mortal lesions suffered by the driver: other passive security devices on board the vehicle and in its superstructure[7] are fitted nowadays in accordance with the best technologies and are available to limit the risk of "injury or death" connected with the "loss of control of a vehicle."

The sequence of events is defined as accidental to the extent that the facts take place in a determined historical sequence; if you think about it, however, many other sequences might have taken place. The blowout of the tire is one of the accidental events that causes the loss of control of the vehicle. It does not necessarily hold true, however, that we can automatically exclude the possible event "loss of control of the vehicle," even if we completely eliminate the possibility of having a blowout, maybe by using indestructible materials in tire manufacture.

Let us try and enter further into the question by going back into the issue of the death of the man occurred during road accident involving the ambulance that was taking him to the hospital for nursing gunshot injuries to his leg.

This is a typical accidental series of facts: by chance the ambulance found a car driver in front; the car driver could have stopped, in the sense that no particular "invariance law"[8] would have impeded him from doing so, but quite accidently he did not bring his car to a halt probably because he did not hear the siren.

The sequence of events can be presented on different levels of descriptive precision, and this has a strong influence on the result of the analysis.

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[7] We refer, for example, to airbags that have not worked correctly, to the fact that the chassis of the vehicle has a flaw in absorbing an impact from the side, or even that the guard rail on the road is not the right shape and/or cannot absorb the impact.

[8] An invariance law is a law that, in clear surrounding conditions, forces the events to develop in a repetitive manner. The law of gravity is an example of an invariance law, which establishes that, on condition it is not above a certain height, a body which has been left free will be attracted towards the ground with an acceleration equal to $9 \cdot 81$ m/sc^2.

We can, therefore, narrate the fact in this way:

> A man is hit by a round of gunfire; he is given help by an ambulance which has to take him to hospital, but, while it is on the way there, the ambulance has an accident and the man dies because he does not reach the hospital for the necessary treatment.

From a sequence of facts set out in this way and by reconstructing the chain of *key events* we arrive at this:

Shot → wounding (requiring hospitalization) → transport in the ambulance → accident involving the ambulance → the ambulance blocked far away from the hospital → lack of treatment → death of the person being transported.

However, the same sequence could be enriched with other particularities, thus bringing out further details in the level of analysis:

Shot → leg wound (requiring hospitalization) → transport in the ambulance → accident in the ambulance → the ambulance is overturned → the patient's head hits against the internal structure of the vehicle → violent contusion to the patient's head → internal hemorrhage of the patient's head → the ambulance blocked far away from the hospital → lack of treatment for the wounded man → impossibility of carrying out operation on the man's head → death of the patient because of internal hemorrhage.

It is clear that although the two sequence of event chains describe the same "story," they give an entirely different depth coverage in "what comes between" the *first event* and the *final event*.

The Concept of Cause in Necessary and Sufficient Conditions[9]

Once we have cleared up the difference in meaning between "first cause" and "first event," we need to take a further step and clarify what we mean by the word "cause."

In layman's terms the word "cause" is carelessly used to mean either the necessary condition or sometimes instead the sufficient condition. We have already seen that in the study of nature events do not limit themselves to merely "happening," but they evolve in an accidental chain from certain conditions.

We commonly distinguish between the "necessary" and the "sufficient" conditions for an event to take place. A *necessary* condition for a given event to happen is an event in the absence of which the event itself cannot come about. For example,

[9] For further discussion, cf. I.M. Copi, C. Cohen, *Introduction to Logic*, Pearson Education, 12th Edition, 2005 (first published 1953).

the presence of oxygen is a *necessary* condition for combustion to take place: if there is combustion, then oxygen is certainly present where it is happening. On the contrary, in the absence of oxygen, there would not be combustion.

Even if it is a *necessary* condition, the presence of oxygen is not, however, a *sufficient* condition for combustion to come about. A *sufficient* condition for an event to occur is a circumstance in the presence of which the event will certainly come to pass. The presence of oxygen is not a sufficient condition for combustion because oxygen can be present but the combustion may not take place. For almost all substances, on the other hand, the simple fact of being at a determined temperature and pressure and in the presence of a certain amount of oxygen becomes a *sufficient condition* for combustion: in such cases we speak about the activation of the combustible mixture. It is clear, therefore, that in cases where there are, without any exclusion, all the *necessary* conditions for the occurrence of an event, each of them "collaborates" in the formation of a sufficient condition that makes the concrete event come to pass.

In other words, our normal use of the word cause is a little confused; sometimes we use it to mean the *necessary condition* for the occurrence of an a phenomenon which has undesired effects. To eliminate such effects, we think, it would be enough to identify one or more conditions that are *necessary* to the incidence of the phenomenon, and eliminate them, so as to eliminate the undesired effect. In this way, a doctor tries to discover what type of virus is the "cause" of a certain illness to treat the patient. If the virus is, in fact, the necessary condition for the existence of the type of illness identified, that is to say, if in its absence the illness cannot develop, the doctor will probably look for and utilize treatment that can destroy that virus.

On other occasions, people use the word "cause" to mean the *sufficient condition* when they wish to create a desirable effect. With this approach, for example, we try to discover the "cause" of the resistance of a given type of steel so that we can produce metals that are even more resistant.

In certain practical situations, the word "cause" is used in yet another different sense. An investigator who needs to establish the cause of a mysterious fire cannot limit himself to pointing out that the fire was caused by the presence of oxygen in the atmosphere; if on the one hand, such a the statement is in itself correct (the presence of oxygen is certainly one of the *necessary* conditions for the fire to take place), it is clear on the other that the aim of the inquiry is that of discovering the "action" which in this particular case has determined the difference between the occurrence or non-occurrence of the event "fire" with respect to the conditions that are normally present.

To avoid confusion, above all as regards the specific meaning that the word takes on in the legal world, when we speak about the "cause" of a specific event we mean the **sufficient cause** that has come about and given rise to that event; in its turn, the **sufficient cause** is to be considered the **conjunction of all the necessary conditions** for the occurrence of the event.

Taken all together, the **necessary conditions** for the coming to pass of an event are called concurrent causes.

Let us have another look at the example of the man who died after the accident in the ambulance that was taking him to hospital. In reconstructing the events with all the details necessary to enable us to define *how* the *status* of the man evolved from his pre-shooting condition to his death condition, we have to keep in mind that:

The **cause** of **death** (final event) is brought about by the internal hemorrhage which developed following the **violent blow** (necessary cause) of the man's head against a steel element inside the transportation compartment of the ambulance, a circumstance this which, **in addition to the omission of an immediate surgical operation** (necessary cause) was **sufficient** to provoke the **death of the man** because of the mortal effects caused by the **pressure of the liquid** spilling into the inside of the cranium (universal "covering" law).

All the concurrent causes, therefore, need to be interpreted as necessary conditions generating the concatenation of accidental events culminating in the death of the patient. In normal conditions the death of the patient cannot be considered exclusively as the consequence of the firearm wound to a leg.

Only as an example, the necessary conditions in the case we are examining might be the following.

- The fact that the first aid emergency service did not arrive in good time, which did not allow for the alleviation of the consequences of the hemorrhage caused by the blow to the head of the patient being transported[10] (this event is subsequent to the overturning of the ambulance);
- The road accident where the ambulance was involved as a concurrent cause of omitted surgery;
- The violent blow of the man's head against a steel element in the ambulance and the subsequent hemorrhage which provoked his death;
- The fact that the man was not fastened in a safety harness during transportation (omission of the personnel on board);
- The lack of due care on the part of the drivers of the ambulance and the car (imprudent action on the part of the drivers).

And the shot? In the example we have been giving this particular type of death was caused by cerebral hemorrhage, not by an infected injury to the leg. We have, therefore, reconstructed that particular type of death with enough precision to permit us to infer that the cause of death is attributable to the spilling of blood in the cranium and not to the gunshot.

[10] This "necessary" condition is clearly connected to the probability that the patient will survive after an operation; we must, therefore, define in terms of "logical" first, and then of statistical probability, the normal implications of a surgical operation carried out to reduce the pressure of blood that has spilled inside the cranium.

Causation in the Scientific Field

In daily life we often use the word "because" in place of the word "how." Feynman starts off with the question, what we mean when we say that we "understand something?"[11]

> We can imagine that this complicated array of moving things which constitutes "the world" is something like a great chess game being played by the gods, and we are observers of the game. We do not know what the rules of the game are; all we are allowed to do is to watch the playing. Of course, if we watch long enough, we may eventually catch on to a few of the rules. The rules of the game are what we mean by fundamental physics [. . .] *If we know the rules*, *we* consider that *we* 'understand' the world. (R.P. Feynman, R. B. Leighton, M. Sands, The Feynman Lectures on Physics, vol. 1, The New Millennium Edition, 1963).

When we speak about the concept of "cause" in a scientific field, i.e., in the sphere of those sciences which aim to "catch on to a few of those rules," we are trying to identify *why* a certain phenomenon takes place in a certain way. Thus, starting out from a number of initial conditions, searching for the cause of a phenomenon means trying to understand the reasons for a certain repetitiveness that we observe in that phenomenon so that we can try to foresee in what way it would evolve towards a state obtained by modifying its initial conditions.

In other words, researching into the reason why a certain phenomenon evolves is the same as determining the invariable laws that put the initial state under observation into relation with its final state.

Now, we need to refer back to two concepts that were introduced in Chap. 1, i.e., the concept of the "trace" (or, rather, the complex of available traces) and that of the single "event," positioning this last inside a precise chain of events.

In fact, the intermediate event that we are reconstructing needs to be connected with an event that is its *predecessor* and an event that is its *successor*. In Chap. 1 we outlined the fact that by correctly reading and interpreting all the traces that have been gathered at the scene of an accident or a disaster we can make a hypothesis about how a given event really came about.[12] This is so because the traces are interpreted as the effects of a given phenomenon that "govern" the event and are to be understood as a variation in the state of the system starting off from certain

[11] In Chap. 1 we already met R. P. Feynman. His famous Lessons in Physics are milestones still today in the physics that is taught in universities all around the world, Lessons in Physics, Addison Wesley, 1963. Starting out from the description of the scientific method and the meaning of research, Feynman's lessons describe the evolution of physics in the XX century, illustrating its connection with other sciences.

[12] Remember that we do not generally have an available filmed documentation of all that happened. If we are luckier, there is some film footage to get down to work on, but for a great deal of other instants in time we cannot have any recordings that can be rewound as we please so we can analyze and extract the instants that we consider the *key events* of the chain. Moreover, even in cases where we have available filmed footage of the fact, it must never come as a surprise if, during a hearing two technical consultants or two lawyers interpret each film still in diametrically opposing ways. For this reason, analysis of the traces becomes of fundamental importance even in cases where we consider ourselves fortunate because we are in possession of a document that allows us to examine the sequence of events in an historical way.

conditions. We clarified, again in Chap. 1 that this logical course is possible only on condition that we can correctly interpret the phenomena that has taken place by identifying the invariable laws that govern the system.

Making inferences about an event starting off from an analysis of traces means understanding "how" a phenomenon occurred based on the interpretation of the signs it left on the scene of the accident as this was taking place.

It should be pointed out that by traces we mean any form of evidence, such as, for example, parts that came away during the failure of a structure, from whose fractured surface it is possible to understand how the material dropped off (for example, if this happened all of a sudden or if the breakage took place slower in time, etc.). Devices for the registration of data are also evidence (i.e., the "black box" on board a place or a ship, or the footage registered on a video camera).

The traces left on the scene are therefore merely elements useful in trying to understand the evolution of particular phenomena that have allowed the system to "migrate" from one state to another.[13]

It should be clear that, if the reconstruction of the phenomena that have taken place is to stand on its own two feet, it is fundamental to apply specific technological knowledge acquired based on training that is just as specific: this specific type of knowledge, this "ability" puts the expert in a position to interpret a trace as the "effect" of something. This second passage requires the expert to know "why" a given effect follows a given phenomenon, i.e., to be fully aware of the causal relationships that allow an effect to be associated to a phenomenon. Let us now take a deeper look at this concept.

Woodward[14] affronts the problem of causal relationships, i.e., he tries to reply to the following question: when can we say that one thing is the cause of another? Precisely he argues that in a complex system "X" can be said to be a cause of "Y" when "Y" is linked to "X" by a causal relationship in such a manner that when we manipulate[15] "X," system responds by changing "Y" just obeying to one or more invariant laws. In that sense, Woodward identifies a causal relationship can be

[13] For example, the braking skid marks left on the asphalt and the presence of other fragments of material found in particular positions allow us, when they are interpreted correctly, to reconstruct the blowout event of the car tire including the trajectory the vehicle followed subsequent to the event. Further analysis could give us even more information about the phenomenon that has taken place: the placement of the fragments of tire material found, for example, at a certain distance from the first skid marks could mean that the blowout took place earlier in time than the braking of the car and not vice versa. The blowout of the tire represents the phenomena that took place at a given instant in time: this blowout is responsible for the alteration of the vehicle + driver system in normal operating conditions to the skidding condition as the driver loses control of the vehicle.

[14] J. Woodward, "*Making Things Happen: A Theory of Causal Explanation.*"

[15] The term "manipulated" is employed by Woodward in the sense that the relationship between X and Y is able to describe properly as Y would change through a causal process that is "activated" by a certain variation of X produced. To produce variation on X, we would be capable to "manipulate" system; manipulation is therefore synonym of experimental test in scientist's words. Scientist provokes system variation by producing conscious modifications of X, so that system replies with variation of Y. Finally scientist reasons whether modifications of system have occurred under invariant laws that links X inputs to Y outputs.

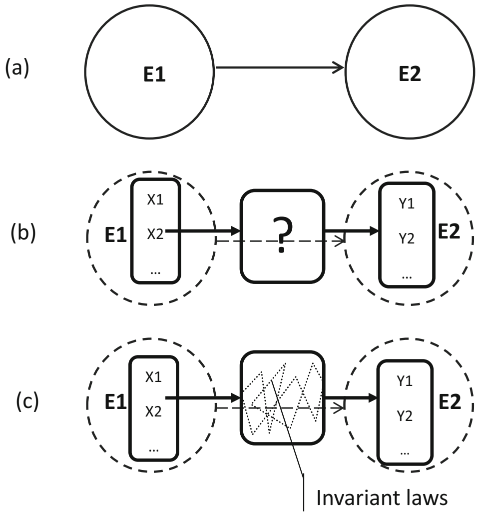

Fig. 3.1 Diagram showing examples of the variables that govern the evolution of a complex system: (**a**) no information are available for correlating repeatable events E1 and E2 that are connected with each other in a certain sequence of events; (**b**) some added information are available in terms of some pieces of information that are represented by a set of observed and measured variables X1, X2, … Xn that qualifies the event E1 and, in its turn, a set of output variables Y1, Y2, … Yn that describes how evolves the event E2 (this provides to us a better description of the system by using measurable parameters); (**c**) the laws that govern the evolution from E1 to E2 is 'understood', as our observation of the basis by which some 'X's' correspond to some 'Y's' potentially allowed us to understand the rules that govern a complex system in its evolution from E1 to E2 state

identified when it is based on invariant laws.[16] In all these cases we can talk about evolutionary processes that are predictable, that is once initial conditions are well known, final conditions can be foreseen.

Moving on from Woodward's generalization we can have a look at the schematic diagram in Fig. 3.1. Figure 3.1a reports two events E_1 and E_2 connected with each other in a certain sequence of events. In the model 2b there is some added information with respect to that found in 2a: the event E_1 is characterized by pieces of information that are represented by a *set* of variables $X_1, X_2, \ldots X_n$, and, in its turn, the event E_2 is characterized by a *set* of variables $Y_1, Y_2, \ldots Y_n$.

To understand what we mean by *set* of variables, we refer back to the case of the patient transported in the ambulance after having been superficially wounded by gunshot fire.

[16] The discovery of "invariant" and "universal laws" allowed scientists to explain why the phenomena and to predict them. Discovering gravitational invariant laws, for example, has allowed humans to construct an object that, by burning the fuel, can receive a force upward with a certain speed to get a specific point in the Earth's orbit and thus to release another object that moves regularly at a certain distance from the ground and transmits our preferred program on our satellite TV.

The events “overturning” of the ambulance and “blow to the head” have been identified in the accidental series as being in sequence (from the point of view of time) and connected one with the other: the event “overturning,” along with the other necessary conditions (the speed of the overturning, the absence of a safety harness for the patient, the fact that there are sharp jutting edges in the internal body of the ambulance, etc.) created the clear and sufficient conditions for the subsequent event “blow to the patient’s head” to come about.

A *set* of variables X_1, X_2, … X_n, able to specify the patient-ambulance system and identify it in correspondence with the instant where the event “overturning” took place could be formed, for example, by the following:

– The conditions of movement of the vehicle (speed).
– The spatial position of the patient inside the ambulance care compartment
– The patient’s conditions as regards harnessing
– The patient’s medical condition (arterial pressure, heartbeat).

The “blow” to the patient’s head could instead be described with the help of a set of parameters Y_1, Y_2, … Y_n which could represent the evolutionary state of the system: these parameters give information about how the system evolved from the event E_1 to the event E_2 received by observing the modification X and Y. Such modifications come about out of necessity in obedience to invariable, universal laws: those that govern the dynamics of inertial bodies in movement on the Earth, and those which explain what happens to arterial pressure or to the heartbeat when the laceration of blood vessels pours a certain amount of blood into the cranium, etc.

For this reason, the diagram in Fig. 3.1b allows us—as opposed to the one in Fig. 3.1a—to give a better description of the system by using measurable parameters. From the measurement of the descriptive parameters of the system and their modification from X to Y we can, theoretically speaking, understand the evolution of the state of the system.

To put it simply, the system under consideration could be seen as a sort of “box,” whose way of working is still unknown; it is, however, possible to associate some “outputs” Y with some “inputs” X, just to use terms typical of electronics.

But what do we mean when we say that we are able to “associate” some X’s that characterize the event E_1 with some Y’s that characterize the event E_2? What does it mean to put effect Y into causal connection with cause X?

Let us take it step by step.

If we refer back to the diagram in Fig. 3.1b, the system under scrutiny can, as we have said, be interpreted as a box: for us, however, this box is still “opaque,” that is to say, it does not allow us to look inside. For this reason we cannot tell exactly “why” certain X’s evolve into certain Y’s.

If we take up Feynman’s example again, we can observe “the movement of the pieces on the chessboard and how the positions of these pieces change in time with a certain repetition,” but we have not yet associated a law that permits us to understand and so foresee how the pieces under observation actually move. The fact that our “box” is not penetrable effectively derives from the or inability to understand the relationships at the base of the evolution of the X’s into Y’s.

On the other hand, just as the repeated observation of the recurring movements of the pieces on the chessboard allows the attentive onlooker to understand the rules behind their passage, so our observation of the basis by which some "X's" correspond to some "Y's" potentially allows us to understand the rules that govern a complex system: and if such rules are grasped, then, just as in a game of chess, we might be able to foresee at least the possible "direction" that the system could take.

To determine as precisely as possible the specific "direction" that the system takes as it evolves, including the entity itself of such and evolution, we need to know something more, besides the rules that govern the system. We also need to have at our disposal a series of notifications—which must be as detailed and as precise as possible—about the state in which the system was running the instant before undergoing "perturbation" and the nature and the entity of that "perturbation."

To understand the sense of what has just been said, let us have a look at its application to an historical case to which we referred in Chap. 1. Galileo used a simple and efficient "system" to carry out measurements of fundamental importance in classical mechanics. The system consisted in a plane with an inclination that could be varied: the plane was well smoothed and honed so as to reduce attrition. He then made a number of spheres of different masses roll down the plane. In the many experiments that he conducted, Galileo measured the distance travelled by the metal sphere from the different corners of the inclined plane. He observed, or rather he discovered that the distance travelled by the sphere was proportional only to the square of the time taken to travel that given distance.

As he wrote himself, he found an unvarying relation expressed in mathematical language that connected the mass m of the sphere, the angle α of the inclined plane and the space s travelled in a time t:

For every angle α that the inclined plane assumes and for any considered mass m of the sphere that rolls on it without attrition, the distance travelled s by the sphere is always proportional to the square of the time t taken to travel along it.

Subsequent to his experiments, Galileo managed to write down the invariable law that governs the system formed by an inclined plane and a sphere. From that law he was able to foresee the result of the ensuing experiment. The unvarying law that "governs" the rolling of a ball on an inclined plane is, therefore, a way of describing a certain repeatability of the measurements made on a *set* of parameters observed during the experiment.

Yet, is this enough to identify the "cause" of the rolling of the sphere? In other words, when we have understood that a sphere of any mass at all rolls on a plane inclined at an angle α, at a speed that is proportional to a time t, does that mean that we have understood *why* the sphere rolls along the plane with that determined law of movement?

The invariable law described by Galileo allows us to grasp "how" the sphere proceeds from its motionless state at the top of the inclined plane and then during a period of time as it is observed in movement. However, it does not help us to understand why the sphere moves when it is left free at the top of the inclined plane. If we are only interested in understanding *how* the system varies, we could even, theoretically, stop now in the enquiry, but this could lead to mistakes in estimates

about the results. Let us imagine, for example, a case with a variation on the one studied by Galileo. Let us introduce, that is to say, a "disturbance" that goes beyond the control that Galileo assured himself of in his verification "system." Consider a rough, un-honed plane and a sphere made of soft material, for example rubber. In such a case, the phenomena of attrition combined with that of dispersion are no longer measurable with the instruments available to Galileo. The law that has been written with the earlier case in mind, and which is valid for those specific conditions, now cannot give us exact results. Yet, we are still speaking about a system made up of an inclined plane with the same angle α, a sphere that has an equal diameter and the same height h of the plane from the top which the sphere is allowed to roll on down.

What has changed?

Certainly not the universal laws which both Galileo's sphere and our own are obliged to obey. In fact, however, we have reached a fundamental conclusion: a prediction about the evolution of a "system" is exact when it is possible to have detailed knowledge about the invariable relations that govern that system—the relations which, if they have been found, give a precise and full correlation between the mass and the angle of a plane with the speed of a sphere's movement along the plane. In any case, we cannot think that every system is so simple, to the point where all the variables are measurable or can be eliminated if they are not (as Galileo did with the phenomena of dispersion).

Think back once again at the example of the car which skids out of control after a blowout to the tire: here the system is much more complex and it would seem practically impossible to determine a priori its precise evolution so as to be able to establish what the car's final position would be, or how its body might move backwards after the collision.

We can say that in general precise predictions about the evolution of systems can be formulated only when:

- The "system" has been perfectly identified as regards all its components that are relevant to the inquiry, i.e., that there are no subsystems or connected systems (which could have an influence on the evolution) that have not been taken into consideration. In the example of the ambulance we considered the "patient subsystem" including the larger system "ambulance-vehicle in movement";
- We have accurately identified all the variables relevant to the description of the evolution of the system and its subsystems;
- We have a clear understanding of all the unvarying laws that govern the system and its subsystems;
- We have a firm grasp of the quantity of non-conservative forces (i.e., the energy that is dispersed by the system while it interacts with the outside environment).

If on the one hand this would bring us to conclude that we can never be able make a perfect model of a complex system,[17] on the other, it cannot hinder us from

[17] If for no other reason that the fact that it would appear practically impossible to have precise knowledge of the conditions which have created a "past" event which we are trying to reconstruct using the traces left by the evolution of that system (cf. Chap. 1).

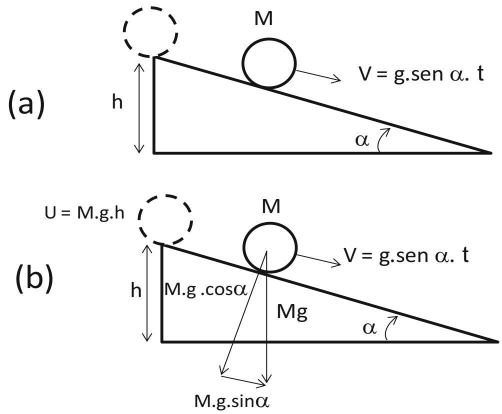

Fig. 3.2 Galileo's inclined plane: (**a**) invariant law that connects mass, angle α, time and speed; (**b**) forces acting on the mass as it rolls along the inclined plane

"getting near" to the solution with appreciable accuracy: this, however, necessarily implies that the aim of our enquiry from "how" the system evolves to "why" the evolution comes about.

We can apply what we have just said to Galileo's inclined plane. Now, we know everything about "how" the system evolved: in fact, Galileo's experience allowed us to predict the speed v reached after a certain time t by a sphere of a mass m left free to roll down a plane from a height h (Fig. 3.2a).

If we are also interested in why the sphere moves and takes on a certain speed at a given moment we have to refer to a number of further facts to be found in the diagram in Fig. 3.2b.

The earth's gravitational field works on the sphere, and this exercises a downward acceleration on a body equal to g (about $9 \cdot 81$ meters to a square second). The earth's gravitational field, therefore, imposes that a body of mass m is attracted downwards by a gravitational force equal to its mass m multiplied by the gravitational acceleration g. however, the presence of an inclined plane "subdivides" the gravitational force acting on the sphere into two component forces: one perpendicular to the plane, counterbalanced by the reaction to the plane itself, the other parallel to the plane and equal to $M \cdot g \cdot \text{sen}\ (\alpha)$ (see Fig. 3.2b).

The sphere rolls without attrition (ideal conditions created by Galileo's experiment), that is, its movement is impelled by this force that we have just calculated, at a tangent to the inclined plane. In agreement with Newton's First Principle, this force, also called the *principle of inertia*[18] is responsible for the change from the state of stillness that the sphere possesses when it is placed in balance and held in position by our hand at the top of the plane. The sphere will roll down thrust by this force: when it has arrived at the end of the plane, i.e., at zero height, it will have moved along a space—that can be calculated in simple trigonometric formulae—equal to $L = h/\text{sen}\ \alpha$. When we know both the force that acts on a body and is

[18] The principle formulated by Newton (perfecting what had already been expressed by Galileo) affirms that to change in any way the speed and the direction where a body is moving you need to apply a force.

responsible for its movement and the space covered in time, we can calculate the energy that has been expended in this movement.[19] In our simple example it is equal to the force—constant in time—multiplied by the total space that has been travelled L. The result that we achieve is that the energy expended (or if you prefer, its *work*), in moving from a height h to zero height is equal to $E = M \cdot g \cdot h$.

Now, if we wish to calculate the *potential* energy, i.e., that which it had when it was in a state of stillness positioned at height h, it is equal to the mass by the gravitational acceleration g multiplied by the height at which it has been placed. This is defined as its *potential gravitational energy*, or, simply, its gravitational potential, and it represents the energy a body possesses because of the mere fact that it is at a certain height from the ground, ready—if it is "freed"—to release that energy, transforming it all into energy in movement (or kinetic energy) or part of it into kinetic energy and part of it into heat. A development of heat appears in cases where, during the movement, the body disperses part of this potential energy because of the attrition produced by chafing against the plane down which it is rolling, in cases where the plane itself and the sphere are not completely smooth.

It is interesting to note that, in the absence of dispersal phenomena (smooth plane and sphere, sphere made of hard material) the energy "consumed" by the movement of the sphere is perfectly equal to the potential energy possessed by the body in a state of stillness.

In other words, the transformation of the energy from potential to kinetic is responsible for the movement of the sphere at a certain speed. In the case we have just described it is finally possible to explain why the sphere moves and why it does so at a certain speed. The sphere rolls down the inclined plane because it is fitted out at the initial moment with a certain part-share of potential energy, which depends on the simple fact that the Earth's gravitational force of attraction is acting on it. As soon as the sphere has been freed at the top of the inclined plane, the force that attracts it downwards gives it movement. This movement is not a casual thing, but it depends on the fact that the body "desires" to give back the potential energy that it has acquired from our hand when we put it at the top of the ramp. Its movement is assured by the share-part of potential energy that transforms itself into kinetic energy. If, on the other hand, we introduce phenomena of dispersion, we need to keep in mind that a part of the sphere's initial energy is absorbed by such phenomena in the form of heat liberated by attrition.

Thinking about the diagram in Fig. 3.1c, looking, in other words, for the causes that regulate the evolution of the system, allows us also to understand the reasons for the imprecision in any measurements that we may want to take. It means really being able to understand the rules of the system.

[19] Generally speaking, the energy expended in the movement of a body is equal to the force that is acting on that body multiplied by the distance it has travelled.

Conclusions

When our field of interest is the reconstruction of an accident, we must take great care in how we handle expressions that are of everyday use in the courts of law, in particular as regards what is meant exactly by a causal relationship and by a concourse of causes.

As stated in Chap. 2, in tracing responsibility for a damaging event, we need to verify whether a causal link between conduct and event exists. Instead, as far as the material reconstruction of events is concerned, no such link appears, as can be seen in Fig. 1.1. We begin looking at this problem in Chap. 4 to try and find a definite solution in Chap. 6.

For now, what interests us, before we can even identify the causal connection between conduct and event, is to develop a method which can allow us to reconstruct the real accidental chain of events. Such a reconstruction must be carried out by an expert, starting out from the study and interpretation of the "traces," and, at the same time, his or her understanding of such a method would allow the expert witness to verify whether the reconstruction is consistent with the factual reality.

As concerns the expert witness, the judge or the district attorney, understanding the method does not, obviously, mean grasping the unvarying laws: the comprehension of the method must lead to our being certain that various specific invariable laws have been considered and which ones they are precisely. In a nutshell, the expert witness, the judge or the district attorney need to be able to know that the reconstruction carried out by the technician is of a nature to be verifiable.

The technical consultant's analysis needs to be liable *in a natural way* to its controvertability, in that this is what is normally inherent in an analysis that has been carried out following scientific methods.

Yet, is it possible to translate all this into a general formulation so that the technician, on the one hand, can structure his work aiming at a consistent reconstruction of the accident, while the expert witness, on the other, is able to follow him step by step?

This is exactly what we are looking at in the next chapter.

Chapter 4
First Level of Sequence of Event Analysis

Introduction

The first aim in the reconstruction of an industrial accident is to "put in line" the events that can rebuild the facts and explain how each episode moves logically forward into the next. In the example of the car that swerved after a tire blowout, we considered the fragments of the tire found in a given position, including the results of the analyses carried out in connection with the morphology and the position of the traces left by the other tires. Results of that analysis might lead us to think that the blowout took place first, and it was only then that the driver instinctually attempted to brake. In fact, the connection between these two successive events is resolved by causal analysis. We have already mentioned more than once a problem that often needs to be faced in the courtroom concerning the substance of statistical associations as evidence. In this connection, we had an in-depth look at the problem to make it clear that statistical inquiries are a necessary aid in the area of legal medicine, i.e., where you cannot always have a detailed understanding of the particular phenomenon.[1] We can now give a complete definition of what we mean by statistical analysis. Looking back at the diagram in Fig. 3.1b in Chap. 3, we can underline the fact that no statistical interpretation can be considered interpretative of any "invariable" law. When invariable law remains unknown (see, once again Fig. 3.1b), it is possible, in certain X conditions to calculate the incidence with which certain Y effects can be observed. For example, there is no invariable law available with which to foresee with certainty the effect of a fall on the driver of a motorbike provoked by the frontal impact with a vehicle (this is the association we are looking for), but a statistical study carried out on a sample of 1000 observed accidents (this is our more or less representative sample of "frontal motorbike accident" population) tells us that there is a y% probability that the driver remains on the motorbike saddle (event Y) subsequent to a frontal impact against a

[1] Cf. Chap. 1, On the debate about the fallibility or the refutability of the scientific method.

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F. D'Errico, M. Dalla Casa, *The Sequence of Event Analysis in Criminal Trials*,
DOI 10.1007/978-3-662-47898-1_4

vehicle when the impact speed is between 35 and 45 km/h inclusive (which is our *set* of conditions X). This means that y% is the degree of repeatability for the association we are investigating, i.e., the one that can logically be expressed in the form: "if X, then Y is probable y times in a hundred." Here is another example. It is one thing to say that, during the blowout of a tire, a car that is going at a speed of 130 km/h will not be controllable, and quite another to explain based on the model and its physical invariant laws governing the dynamics of a vehicle that the loss of adherence of one of the vehicle's four points of ground contact creates an unbalance in the forces of road-vehicle and that this unbalancing can gave rise to the rotation of the vehicle on its own axis. This rotation would be ungovernable only by utilizing the brake pedal and the steering column. These two statements are totally different, in their content and weight. As soon as a good lawyer has heard the probabilistic relationship formulated by the technical consultant of the opposing party, he would reply with other statistics, saying: "It is not possible to support your case. Come on, you are referring to the only case we know of an accident caused by the blowout of a tire made by Gummy Corporation which happened on a motorway! What is the probability of such an event? We are talking about one case in a million of tires sold in the world this year!"

What frequently happens is that our attention gets bogged down in useless statistics which, when they are employed in this way, give no help in understanding the law that modifies the state of the car from "running in stable conditions" to "skidding" and "hitting" against the rigid guard rail. We do not generate any understanding about the physical causes of the anomalous blowout of the tire. Thus, we are still farther from the diagram in Fig. 3.1c, which allows us really to reconstruct the causal nexus between each previous event and its successor.

The Sequence of Event Method or First Level SEA

Discovering the existing relationship between an intelligible "effect" or *trace* which has been left on the ground and the "phenomenon" which has caused it is the obligatory passageway towards being able to grasp the causal link between two events in a sequence resulting in an accident. Let us try to clarify. For the sake of simplicity we repeat in Fig. 4.1 the general diagram which we already introduced in Chap. 1 to explain the existing difference between a *coherent* chain of events and a *consistent* chain of events. In the lower part of the diagram we can see that there are a number of rectangles, each of which refers (making use of an arrow) to a given event. It goes without saying that the event is symbolized by the circle. Each rectangle represents the *set* of *traces* that has been used to be able to formulate the hypothesis of an event that can be explained logically under specific universal laws (*coherent* event). It follows that if we wanted to represent the logical process carried out by the investigator, we could sum them up in the four stages, as follows:

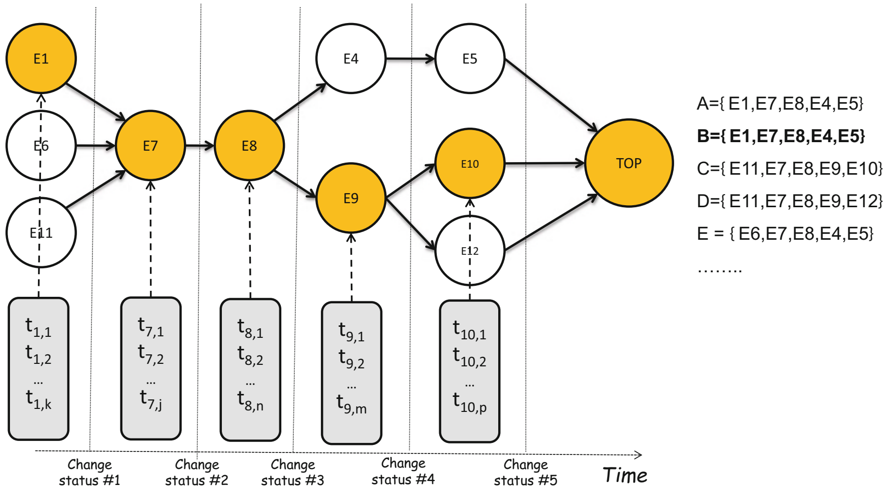

Fig. 4.1 A general diagram that shows the different events placed in a coherent reconstruction and the only sequence that is identifiable as consistent with the facts in that it can explain the entire set of evidence $t_{j,k}$ gathered on the scene

1. **Starting out from the traces**, the investigator *abduces* a theory that would explain the *phenomenon*, able, that is, to elucidate its presence on the scene;
2. As the phenomenon is governed by universal laws, he can now be able to **abstract** which **universal laws** are involved;
3. From the unvarying (or universal) laws he has subsumed in reference to the particular phenomenon which he has identified, the investigator will also understand (moving backwards or forwards) how the *system* has evolved. As we put it, **understanding the evolution of the system** means identifying the relevant changes of state, i.e., the key events; this allows us, therefore, to make a hypothesis about another event (predecessor or successor) which is **causally connected** to it;
4. Once he or she has formulated the hypothesis that sees an event E_i as causally connected with another preceding event E_{i-1} or with a subsequent event E_{i+1} which has already been identified, the investigator must now start on the **verification phase**. If the hypothesis about the *coherently* connected event is true, this will now allow explanation of all the *traces* that refer to that particular event.

The process is repeatable as it aims to refine our understanding to increase the precision with which we can reconstruct. In reconstructing there is no preferential "direction" to follow, i.e., we do not always go from a *top* event and gradually move backwards. Sometimes it can be easier to start off with traces that are immediately interpretable and begin to formulate hypotheses of reconstruction on a certain number of key events in the chain that we have found even "at a distance," only then beginning to reconstruct other connected key events, so increasing bit by bit

the number of traces open to interpretation. They only rule that we have to impose on ourselves is that in the end all the available traces must have found an interpretation and all the connected events that we have reconstructed need to have their presence explained.

Our *traces* are therefore at the same time the point from which we begin our reconstructive inquiry (abductive phase) and the point towards which the inquiry must always return to validate the hypotheses we have made (inductive phase). In this sense, when using *first level SEA* we intend to refer to the basic diagram given in Fig. 4.1, a guideline that helps us to go through the four fundamental steps (see points 1–4 given above) which translate for our specific purposes the (repeatable) three phase scientific method as discussed in general terms in Chap. 3.

The expression "first level" underlines, primarily, that the reconstruction method is characterized by an inescapable dependence on the phase where the *traces* are interpreted (*abductive phase*), while it also suggests that this is not the only level to which we will refer.

Let us have a look at the direct advantages deriving from the application of *first level SEA*. First, it aims to make sure that there can be no forced reduction in the number of *traces* used in the reconstruction phase, maybe even neglected only because they do not "square" with the work that we have carried out. Given that we are in possession of the competences to interpret them, when we say that some of the traces do not "match," it means we are implicitly admitting that the reconstruction we have carried out as our first attempt is in fact a failure. The reconstruction of an accident always have to "match" with the traces gathered at the scene as they are the only guarantee that we can verify the hypotheses we have made concerning our reconstruction of the events. They are, that is to say, the only element that is able to "bring us back" to the reality of the facts. For this reason all the traces need to be explained (*inductive* or verification phase) as we recreate our abstract evolution (*deductive* phase) of the system based on the phenomena that have previously been identified. It can always happen that the traces have not been interpreted correctly, but this brings us back to our point: a trace that has been neglected, because it has been interpreted wrongly or because it does not "fit in" with the reconstruction we have carried out, is never a "mistaken" trace. It is, rather, the symptom of a reconstruction that is (still) not right and which needs to be re-worked.

Now, if, on the one hand, the dynamics of a complex accident are inevitably complex to define, one basic concept (we propose as a general guideline as concerns the reconstruction of accidents) is that the prosecutor, the judge or the attorney must verify: (a) that the incident has been reconstructed as a (con)sequential chain of key events, (b) that all the events made available by the work carried out by the Police or Forensics have been taken into consideration. As regards this last aspect, the assessments made by a non-technical supervisor need not be all that difficult: he has to verify how many traces have effectively been used and how many have not, and he also has to ask for explanations on "how" the evidence has been managed. In other words, he has to verify first that a particular trace has been used to infer a particular phenomenon and that it (or any other that is available) has been applied to

verify the hypothesis of reconstruction that has been formulated in reference to a specific key event.

It can happen, however, that there is evidence, but that it cannot easily be interpreted. This should often prompt the public prosecutor or the judge to widen out the areas or disciplines where the technical consultants are involved to integrate the missing competences that do not permit the experts already at work to understand a part of the traces that have already been found (Chap. 7). The fact is that any arbitrary reduction in the number of traces under consideration can blur the precision of the reconstruction. In such cases we speak about a loss of consistency in the proposed sequence of events.

The Limits of First Level SEA

It is, therefore, easy to visualize the methods used in *first level SEA*: looking at the generic scheme as set out in Fig. 4.1 we can simultaneously keep in mind all the key elements in our inquiry.

– The *traces* or pieces of evidence from which we **start out** in the *abductive* phase as the hypothesis is being formulated and to which we will **return** during the *inductive* phase of verification as we corroborate the reconstruction of the event that we have carried out from our original hypothesis;
– The *key events* which become clearer and clearer and more and more causally connected in a coherent way, i.e., logically deduced based on the abstractly presumed evolution of the system according to specific unvarying laws that have been identified from the traces.

Despite all this, we still have not given a reply to the question connected with the identification of a causal relationship between the behavior of one (or more) agents and the prejudicial event. As we will see in a moment, the fact of the matter is that, if, on the one hand, *first level SEA* gives valid support to the technical consultant who has to reconstruct the facts that have led to a complex accident, it does not, on the other hand, give any answer to the needs of the attorney or the magistrate who has to define what behavior is to be considered the cause of the prejudicial event. To put it even more clearly, carrying out counterfactual analysis based exclusively on *first level SEA* to verify whether a certain conduct has or has not had an influence on the evolution of an event can usually lead to erroneous results as regards tracing responsibility.

We now try to explain this idea a little more fully, and, to do so, we can go back to our example of the death of the patient being transported to hospital in an ambulance because he has been wounded by a shot from a firearm. We are now finally able to represent the chain of events in our example giving all the principle elements that we need in a typical *first level SEA* diagram, i.e., the *key events* and the relative *qualifying evidence* (the *traces*). The result obtained is given in Fig. 4.2.

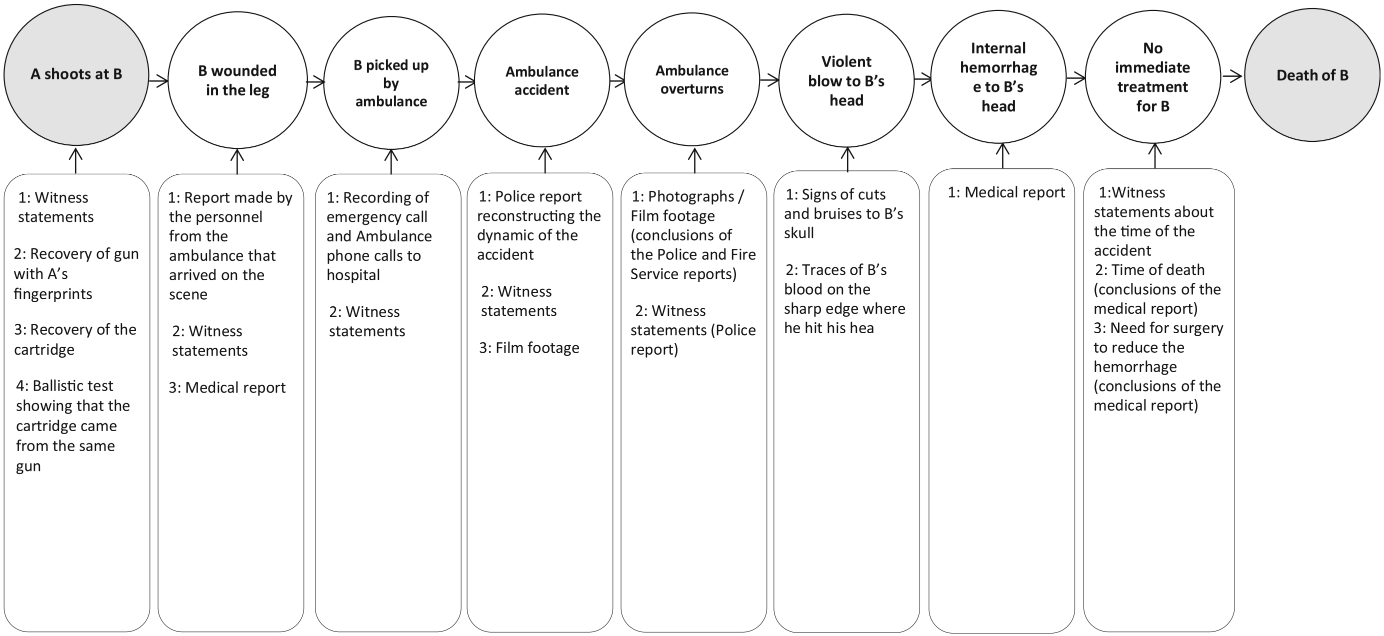

Fig. 4.2 First level SEA reconstructed based on the available traces (cf. the lower part of the diagram)

Now, we need to make two important observations. Note, first, that in the diagram in Fig. 4.2 we have inserted the event “A shoots at B” as the first event; second, the arrows connecting a previous to a subsequent event are all of the same type, i.e., they are one-directional, going from left to right. We can look at these two questions together, because this is the only way to realize what problems come up when we make imprecise use of the reconstruction of the chain of events in an accident, whether it is carried out using the SEA method we are proposing here.

The arrows between events seem to communicate a direct causal relationship between one previous event and the next. Seeing as the arrows set out here are all exactly the same, they give the mistaken idea of an equivalence in the interdependent relations between one event and the subsequent episode.

There are, of course, some previous events that necessarily lead to ensuing upshots, but there are others that do not, because for that to occur we need to establish some further essential conditions. In our example, the event “A shoots at B” does not necessarily imply death, and in fact B’s leg has only been injured in a limited, superficial way. We can say the same thing regarding the two events “ambulance accident” and its “overturning”: an accident involving an ambulance does not necessarily imply that the vehicle will overturn. Just as the event “blow to B’s head” does not necessarily originate in the “overturning” event. If he had been well strapped in, B would not have undergone the head blow against the sharp edge; or if the internal architecture of the ambulance patient care compartment had been structured in a different way so as to prevent an occurrence of the kind, there would have been no blow or the wallop would have been lighter.

We could continue in the same way. But on the other hand the event “delayed treatment” must be linked with the “death of B.” We need, therefore, to differentiate in some way a causal relationship between two events that is of an “ineluctable” nature from a situation where there is a simple relationship between them which does not necessarily imply that one event is the consequence of the other. We have already spoken in Chap. 3 of the symbols used in Boolean logic, and as these can be of some help here we will give them in synthesis in Fig. 4.3.

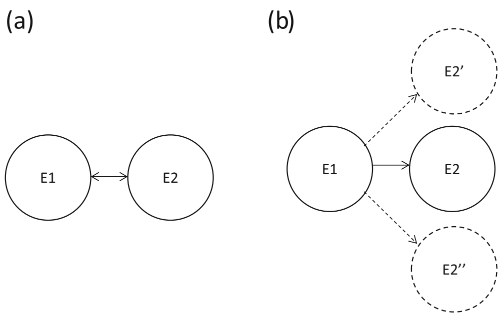

Fig. 4.3 Diagrams showing the two types of relationship between event and event: (**a**) the event E2 originates as an ineluctable consequence of E1; (**b**) the event E2 is only one of all the possible events originating in the evolution of the system starting from E1; For E1 to evolve into E2 we need to establish the existence of further external conditions

In the diagram in Fig. 4.3a the double arrow suggests that event E1 will necessarily (i.e., with an extremely high logical probability) be followed by the event E2, even without the intrusion of any other external factors. As against that, the diagram in Fig. 4.3b gives the intuitive suggestion that a number of different almost equally probable events could have followed event E1, among which E2 is an event that is consistent with the traces that have been gathered. People working in the legal sector could be induced into error by the mistaken interpretation of the types of interdependent relations existing between one event and another after having placed the event "A shoots at B" at the beginning of the sequence. We must now try and understand how such mistakes can come about.

The technical consultant is illustrating the reconstruction made in agreement with the diagram in Fig. 4.2. If now, the legal worker (deliberately overlooking in this specific instance any kind of inquiry into the psychological attitude of the agent) applied to the case the diagram proceeding from counterfactual analysis, he would be forced to trace the prejudicial event "death of B" back to the earlier event "A shoots at B." For example, the lawyer might tend to reason in this way:

> If the accident [involving the ambulance] hadn't happened, B would have received the necessary treatment and would not have died.
>
> On the other hand, if the journey in the ambulance had not been made necessary, B would not have been involved in the accident.
>
> Looked at in this way, if A had not shot at B, there would not have been any necessity to take him for treatment in an ambulance and so B would not have been involved in the accident.

In this form of reasoning there are a number of different mistakes, some of which have effectively been induced by the incorrect application of sequence of event analysis. Let's take one thing at a time.

The legal representative is reasoning in the way he is used to doing, but he is neglecting the fact that counterfactual analysis is specifically indicated (Cf. Chap. 2 for details) to identify a causal relationship between *conduct* and *event*, not between *event* and *event*. In fact, when he mistakenly applies it to the chain of events in our example, he will inevitably be led to trace the primary cause of the decease to the prejudicial event "A shoots at B." In connection with this example, we have already argued in Chap. 3 that a careful and clear-cut reconstruction of the facts starting from medical and legal analysis into the causes of B's death leads us to conclusion B's death has been caused by a specific event, the "internal hemorrhage" to the cranium, which is not a possible clinical consequence of a superficial gunshot wound to the leg. That is to say, the internal hemorrhage is as a "phenomenon" independent of "A."[2]

[2] I.e., an independent causal sequence has been established, which effectively interrupts the causal relationship between the event B's "wound to the leg" and his death.

However, we need to remember first that the reconstruction made by the technical consultant is a connected series of accidental events linked one to the other to explain the causal relationships between a preceding and a subsequent event. We are still not able at this point to say anything about the causal relationship between *conduct* of human agent and *events*. If the legal representative "moved" in the same way as the technical consultant to trace causal relationships between *conduct* and *event*, this would inevitably lead to mistakes like those that have been made in the preceding example.

The first important conclusion, therefore, is that the legal representative and the technical consultant's levels of intervention **must remain rigorously "separate"** in the SEA diagram.

The second important conclusion is something we have already introduced when we were talking about the types of relational interdependence there is between one event and another. As we have already said, in logics' words these relationships can be either "necessary and sufficient" implications (E2 originates ineluctably in E1) or E1 does not necessarily imply E2 unless we are in the presence of further conditions. In cases where these "other conditions" consist in other types of behavior (carried out by another or by the same subject), such conduct must be considered the necessary condition for precisely the E2 event (among the three logically possible occurrences, cf. Fig. 4.3b) actually to come about. This is, therefore, the crucial point of connection between the event–event chain as represented in E1–E2 (cf. once again Fig. 4.3b) and the external conditions, the types of behavior, that have made such a sequence possible, or which, in any case, have done nothing to impede it. To sum up: on the one hand, by basing his work on the salient traces, the technical consultant arrives at the conclusion that the Event E2, one of the three that are logically possible according to the diagram in Fig. 4.3b, is in fact that which actually took place. One the other hand, the mono-directional relationship supplies the legal representative with further precious information in tracing responsibility: the E2 event could concretely have taken place only in subordination to the onset of additional external conditions. If these external conditions coincide with the conduct (an act or omission) of a certain subject, on condition that the causal connection between the behavior of this subject and the occurrence of the E2 event has been demonstrated, such behavior is to be held a necessary condition in the development of the accidental chain of events that led in the end to the final event. Keeping in mind that (Cf. this chapter) when using the term **cause** we are identifying the **sufficient condition** because of which an event occurs and because this in its turn is to be considered the **combination of all the necessary conditions** for the event itself to transpire, we can say such conduct necessary for E1 to evolve into E2 is certainly a **cause** or a **contributory cause** of the E1–E2 sequence.

We need, lastly, to be careful about the type of *primary event* from which we make the sequence of events begin: defining "A shoots at B" as the *first event* as given in Fig. 4.2 (i.e., as the event which triggers the subsequent events) is misleading because it mixes up "conduct" with "event." This wrongly suggests in turn that the expert witness should go back to the "first action" from which everything originates. Someone is always responsible for the first action; but this is far from establishing whether he is really responsible for all the events subsequent to his conduct, independently of the true causes of B's death.

From these specifications, it therefore becomes necessary to modify as follows the diagram proposed in Fig. 4.2:

1. To connect two successive events single or bi-directional "arrows" are introduced, chosen from the type of interdependence existing between the two: a double arrow is used if the sequential relationship between one event and the next contains a high logical probability. In opposite cases there is a mono-directional arrow from left to right, i.e., pointing towards the chronological order of the events. Notice that once the evolution of the system from preceding to subsequent event has been determined (subsumed based on invariable laws, cf. Chap. 3) it is also possible to judge the type of causal relationship to which the two events belong, i.e., whether the relationship is sufficient *in itself* (bidirectional arrow) or whether you need further necessary conditions which are external to the preceding event (mono-directional arrow). The causal *event-to-event* connections given as a mono-directional arrow (Fig. 4.3b) suggest that it has become essential to identify these further external factors (e.g., the behavior of another subject) that are **necessary** to the evolution of the **accidental chain** of events in agreement with the concrete case;
2. The action "**A shoots at B**" is repositioned outside the **first level** of the sequence. As it is an "action," it is an element of **conduct** not an **event** describing the evolution of the system. In this way, a new descriptive level has been identified in the evolution of the events.

If the diagram in Fig. 4.2 is reworked in agreement with the corrections given in points 1 and 2, you arrive at the diagram in Fig. 4.4. This new level, which we call **conduct level** finally allows us to consider the implications that certain actions or omissions might have had on the development of a particular event in the sequence. We are now able to analyze what different types of behavior when taken together create the sufficient conditions needed for the system to evolve along the sequence of events.

In the example in Fig. 4.4, for instance, the action "inefficient and delayed arrival of back-up first aid units" in combination with the action "late arrival of the Fire Service to open the patient care compartment" are the sufficient condition for the fact that B could not be taken as quickly as possible to the Hospital Casualty Department for an emergency operation.

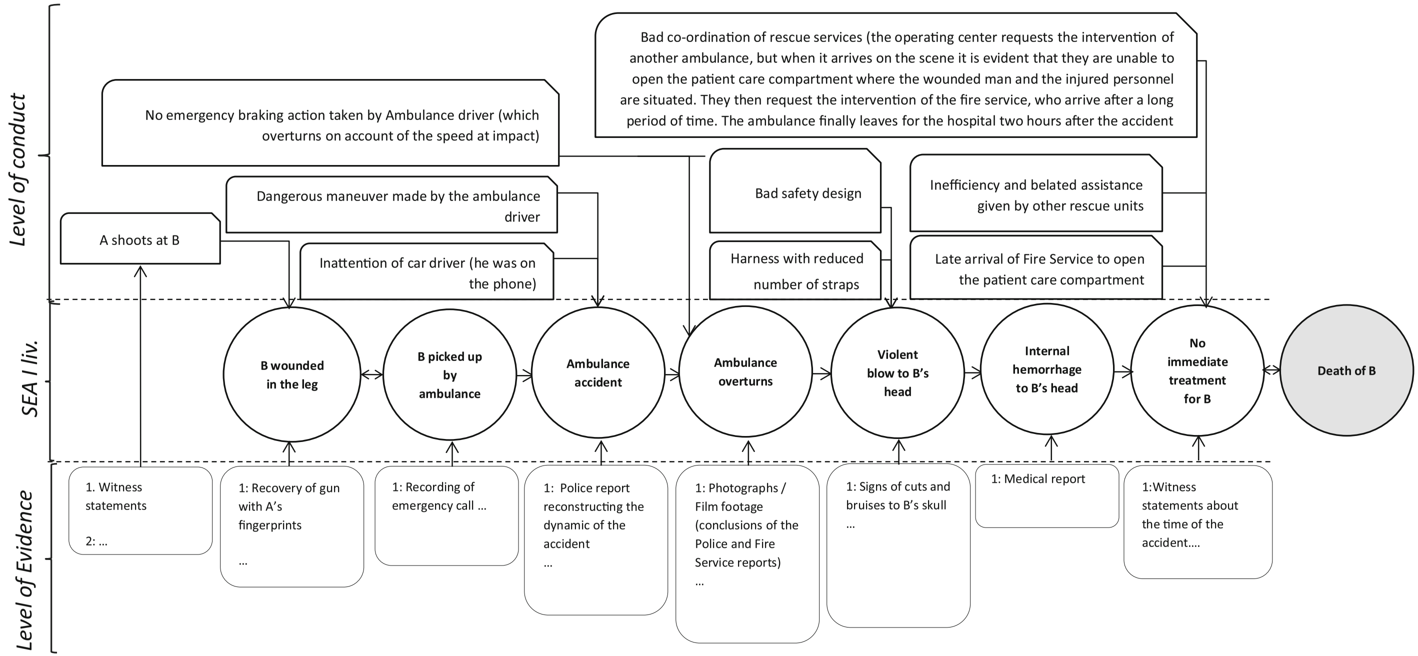

Fig. 4.4 SEA tiers of Fig. 4.2, as amended by the type of relationship of interdependence between event and event

Conclusions

First level SEA is an instrument created based on the three-phase iterative method, typical of any scientific enquiry. The use of a scientific method gives the only real guarantee we can have of reconstructing the events of a complex accident in a way that is really consistent with the facts. First level SEA is made up of a (basic) sublevel from which the enquiry originates: the interpretation of the "traces" gathered at the scene of the accident (in the diagram in Fig. 4.2—and in its more developed form in Fig. 4.4—this sublevel is defined as the "level of evidence"). From the interpretation of the traces as the effects of a certain phenomenon, hypotheses are then formulated which need to be open to verification so that the hypothetical sequence of the accident can first be consolidated and then refined with further hypotheses and verifications, or rejected on the grounds of alternative hypotheses that respond more closely to the evidence.

When the accidental sequence of events has been verified from all the evidence available, we can illustrate it in a diagram as a long chain of key events, each of which is consistent with the available *sets* of *traces* (cf. Fig. 4.2).

Such a diagram would, however, only partly respond to our fundamental objective: the reconstruction of the accident with the aim of identifying criminal responsibility; i.e., the identification of the conduct that has played a vital role in the occurrence of the prejudicial event. The types of interdependent relations between a preceding and a successive event, whether this should be "inescapable" or merely "logically possible" is represented by the type of connecting arrows between event and event: a two-directional arrow indicates that the preceding event necessarily implies (i.e., with extremely high probability or even certainty) the subsequent event, which means that there is no need to insert further particular conditions; a one directional arrow from left to right indicates that the subsequent event is one of those possible but it can only come about in the presence of certain other specific conditions (conditions, that is to say, that have been "favored" in the case of active behavior, or that has not been impeded in the case of omission).

To evaluate these further conditions which are sufficient to make a system evolve from one state to another, we go to work on a level that is superior to the first: this is the "conduct level" as shown in Fig. 4.4.

This is also the level on which the expert witness and the magistrate begin their work of tracing responsibilities.

However two new questions make themselves felt at present: if subject A's conduct set up a chain of events but is intermediate in the sequence that leads in the end to a damaging event, is it possible to say that subject is responsible for that event?

(continued)

We have reacted implicitly to this first question by introducing a particular system of symbols into first level SEA between a preceding and a subsequent event. By using a one-directional arrow to connect a preceding event E1 to a subsequent event E2 we mean to imply that E2 does not necessarily stem from E2 but might do so if other conditions are established.[3] If the connection between E1 and E2 is "one-directional," that is to say, logically possible, this means that the E2 event is conditioned in its concrete evolution in subordination to other necessary circumstances (or conditions) for it to migrate from E1 to E2. In such a case, the action A which causes the event E1 should not be considered a sufficient cause for the event E2. If we turn this on its head, we can say that, seeing as E2 is the damaging event for which we are searching out the responsibility, the one-directional connection between E1 and E2 establishes that A's conduct, which is the cause of E1 is not able to create the "point of no return" conditions swinging the system towards E2. That is to say, the chain of events that could have had a direct influence on the evolution of the system from E1, and which culminated in the damaging event E2, thanks to acts that could have been carried out (by other people or by the same subject). On the other hand, A's conduct is necessary for event E1 to come about, which could then under the influence of other conditions evolve into E2. If it be the case, therefore, that other conduct on the part of a subject B is recognized as an action or omission which was capable of provoking or not putting a stop to the evolution of E1 into E2 even if there are other possible alternatives (cf. the diagram of Fig. 4.3b), B's conduct is considered equally necessary as A's to arrive at the event E2. In other words, **the set of A and B's actions** creates **the sufficient conditions** for the chain E1–E2 concretely to occur. The action of both A and B are therefore to be considered in conjunction as **causes acting together** to create event E2.

The second question is this: what type of actions and/or omissions should we examine? Which subjects should we consider?

Before we can answer this last question, and our reply will be leading on to the SEA method articulated on three different levels as far a conduct is concerned, we must first introduce the concept of organizational accidents much in use in modern literature dealing with complex accidents. This is the specific subject of Chap. 5.

[3] These further "conditions" are created by additional actions that influence the evolution of the system from E1 towards E2: they can be "read" by looking at the superior level of SEA, which describes conduct.

Part II
From Scientific Proofs to Reconstruction of Multilevel Liability Pattern in Organization

Chapter 5
The Analysis of Accidents Using a Multi-Level Approach: Organizational Accidents

Introduction

After a serious accident we always ask ourselves an unnerving question: is it really possible that an involuntary human error can cause a disaster of these dimensions?

In a new study Catino took an in-depth look at accidents that have occurred on the Italian railways, in particular at what happened in January 2005 in Crevalcore, Italy.[1] This study was carried out in agreement with literature studying the peculiarities of complex accidents. Down the years, in fact, it has become clearer and clearer that the accumulation of serious errors egged on by critical levels of organizational problems[2] occur principally in a system that is characterized by bureaucratic-type[3] safety measures. Catino claims that we are here talking about errors that are predictable in organizations equipped with error management systems able to highlight the most critical situations and to adopt measures of correction.

To understand what we mean by critical situations, we could start by saying that no one today would ever think of basing the security of an airplane only on the eyesight and the attention of the first and second pilot in the cabin. In the 1950s and 1960s people could make do with flying with pilots' visual flight with the assistance of a radar or other rudimental instruments, but today no one would even be willing to board an aircraft that still used such old fashioned technology.

Yet there have been serious cases in aeronautics in which a land-based surveillance radar stopped working although it was there to assist pilots in taking off or landing in conditions of zero visibility, and this meant that the pilots could only use their eyes and ears.

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[1] M. Catino, "Incidenti tecnologici nel trasporto ferroviario," Ergonomia, n. 1, pp. 36–51, 2006.

[2] Cf., for example J. REASON, *Human Error*, Cambridge University Press, London 1990.

[3] R. Westrun, Social Factors in Safety Critical Systems, in F. Redmill – F.- J. Rajan (edited by), *Human Factors in Safety Critical Systems,* Butterworth – Heinemann, London 1997.

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F. D'Errico, M. Dalla Casa, *The Sequence of Event Analysis in Criminal Trials*,
DOI 10.1007/978-3-662-47898-1_5

This is exactly what happened, for example, in the disaster at the airport of Tenerife in 1977, still considered today the most serious accident in the history of civil aviation. The accident took place because of a collision between two passenger Boeing 747 Jumbo Jets on the runway of the airport of Los Rodeos (today renamed Tenerife North Airport) on the Spanish island of Tenerife, one of the Canaries.

The final tragic count was of 583 victims, i.e., all the 248 passengers on board KLM flight 4805 including the 335 victims of Pan Am flight 1736.

Thick fog on the airport's only runway was certainly the element that triggered the mistake made by the pilots of the two flights: as it was just taking off the KLM flight crashed into the Pan Am airplane that had been given authorization to taxi down the same runway in the opposite direction.

Can we really think that it is possible to attribute a disaster of this kind only to the lack of visibility and the ground staff's bad English pronunciation?

In fact, from what emerges in the official reports carried out by the investigative bodies, there had been more than one moment of incomprehension with the control tower: these communication problems convinced the first officer of the KLM flight to start up the engines for the take-off phase while the Pan Am flight was still taxiing along the runway to reach the pre-threshold point and take up position correctly behind the KLM flight.

This is not really totally different from what happened at Los Angeles International Airport on 1 February 1991: on that occasion US Airways Flight 1493 collided as it was going through the landing phase with a small Metroliner aircraft belonging to SkyWest which had mistakenly gone into position on the same runway, ready to take off. As the ground-based Air Traffic controller for local flights immediately admitted this was caused by his distraction because just a few minutes before he had authorized the take-off of SkyWest's Metroliner on the same runway where the US Airways Boeing 737 was just landing.

Lately in Italy a similar airline disaster happened at the Linate airport of Milan. On that occasion 118 people died in the impact between the Scandinavian company SAS's airplane as it was taking off and a small Cessna with four people on board, which had by mistake entered the runway in conditions of almost zero visibility because of thick fog.

There is no doubt about the existence of human error in these three disastrous episodes. And yet we cannot isolate human error alone. Even if we return later to the three events we have just described and the interesting conclusions reached by the investigative commissions, it is a good idea to underline at once the wider evaluations made concerning the accidents. The inquests did not limit themselves to the identification of the human error that had been made: having gone through that, the investigators went on to ask the question: "why were such mistakes made?"

What investigators were trying to figure out was the following: if such disasters originate in human error, and seeing as it is quite reasonable to think that mistakes of that type have always to be kept in mind—does this mean we have to resign ourselves to seeing others cases of the same kind in the future?

What goes for aircraft goes for other things as well. It would be difficult today to accept that the safety of the passengers on board a railway convoy or of those that

live along a railway line should be delegated exclusively to a human being. The eyes and ears of an experienced train driver or all the care and attention given by a specialized technician when he is testing the structural integrity of a train just cannot be taken as standards of safety. If, for example, the principle really held true that the security of a whole convoy solely depended on one check carried out by a technician—well, I do not think anybody would get on a train again.

It is true that the decision to delegate the assessment of structural integrity to one last crucial operation creates an extremely dangerous "bottleneck" as far as safety is concerned as it concentrates a high degree of risk on one single operation. However, such a result stems from work plans that show that the security organization is inefficient, and this in its turn originates from ineffective risk analysis and evaluation.

The Three Models of Organizational Accidents

Analyzing the accidents and disasters in organizations, three are the explanatory models which have been developed since the 1970s to give an account for the causes of an accident. Each model has its own idea of the nature of the error leading to the accident.[4]

The first model, which literature describes as "traditional," is based on an explanation of an engineering or formal juridical type, i.e., it explains the accident as the result of a failure in the technology or as a deviance from what was foreseen in the standard in reference. The roots of this model go back to the 1960s or 1970s, when, that is to say, modern technologies or control systems were in full evolution and it was thought that the job of containing the risks connected with the use of machinery had been delegated to the machines themselves and when inquiries into accidents tended principally to consider technical regulatory aspects as the causes of accidents and the measures taken to improve security were in fact directed at minimizing the failure of technology.

The second model based on the individual was developed in the 1970s after a number of serious accidents that began to shift attention towards the human component which, because it is fallible, can often create errors as a consequence of workloads that are too heavy or badly designed or show little planning in terms of the interface that creates communication between man and the machine or unreliability in levels of attention, interpretation or information. According to this model, an error is created by a cognitive overload that lowers the level of attention.[5] Rasmussen and Reason made the first steps in the field when they claimed that human error is the expression of failure in the sense that it is the unsuccessful

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[4] M. Catino, Organizational Myopia: Problems of Rationality and Foresight in Organizations, Cambridge University Press, 2013.

[5] M. Catino, *op.cit.*, 2013.

achievement of the results that were expected from a planned sequence of physical or mental activities.[6] To find a solution it would be necessary to redefine workloads (so as to make them more coherent with the individual's cognitive capacity), and of the man-machine interface and the work place.[7]

Lastly, the third model is "organizational or socio-technical." It only began to be developed in the 1990s[8] triggered off by the accidents at Three Mile Island, Bhopal, Chernobyl and the disaster involving the Space Shuttle Challenger.

This alternative model, which seems more a synthesis of the two preceding ones rather than something completely new, centers our interpretation of serious but foreseeable accidents and disasters as real organizational failures. The interaction is on various different levels: technological (first model) human (second model) and organizational (third model), caused by an insufficient structuring of technological resources in assistance of the human element in operating activities.

With this model we have, therefore, entered an epoch which considers that serious accidents can happen not only because of the fact that the rules regulating the existing procedures in an organization have been violated, but sometimes also because of those same regulations and procedures, which, if they are ambiguous or unsuitable, can actually favor the creation of mistakes or accidents.[9]

In agreement with literature in the field carried out by Reason,[10] we consider organizational accidents as a result of the concatenation of two elements: *active errors*, made by the people who are in closest contact with the task to be performed, and *latent factors*, which are of an organizational, administrative or management nature, carried out by people or structures that are often far away as regards both time and place from the actual scene of the accident.[11]

For example, safety problems deriving from little or ineffective maintenance (with the obvious exclusion of cases in which there is willful misconduct) human or instrumental errors become devastating when the organization itself has not foreseen suitable "protective networks": such safeguards which should always be

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[6] J. Rasmussen, *Safety Control and Risk Management*, in NPPCI Specialists' Meeting on the Human Factor Feedback in Nuclear Power, *Implication of operating Experience on System Analysis, Design and Operation*, L. Hansson and B. Andersen, ed. Risø National Laboratory, Roskilde, 1987 and also J. Reason, *Human Error*, Cambridge University Press, London 1990.

[7] M. Catino, *op.cit.*, 2013.

[8] B. Turner – N. Pidgeon, *Man-Made Disasters,* 2nd ed., Butterworth – Heinemann, Oxford 1997, C. Perrow, *Normal accidents: Living with High-Risk Technologies*, Basic Books, New York, 1984, P. Shivrastava, *Bhopal: Anatomy of a crisis*, Ballinger Publishing Camp., Cambridge 1887, D. Vaughan, "Autonomy, interdependence and Social Control: NASA and the Space Shuttle Challenger," *Administrative Science Quarterly*, 35 (2) pp. 225–257, 1990, D. Vaughan, *The Challenger Launch Decision: Risky Technology, Culture and Deviance at NASA*, University of Chicago Press, Chicago, 1996.

[9] M. Catino, *op.cit.*, 2013.

[10] J. Reason, *op.cit.*, 1997.

[11] M. Catino, *op.cit.*, 2013.

present to reduce the consequences of error in parts of the process, which can act as dangerous "bottlenecks" for the safety of the system.

Everything at present rotates around making a careful and adequate plan for a Security Management System: the main task of any such system must be to define, design, activate control and re-modulate the security measures, acting on the need to set up a complementary series of measures that can prevent damage in high risk situations, even when there has been a possible human or instrumental error.

This model needs to be developed starting off from an analysis of the risks, and its components must foresee an ethical code, an organism of vigilance, a penalty system and a structure for the management of health and safety. A number of internationally applied standards occupational health and safety management systems have been proposed. The English standard BS OHSAS 18000 is a guideline for several national rules in many Countries.

The BS OHSAS 18000 is specifically applicable to any company that wishes to establish a Safety Management System to eliminate the risks associated with their activities or to reduce them to their minimum, both for their employees and whoever might be exposed to such risks. It is also designated actuate, maintain and continuously improve the security control system.

We take a closer look at the problem of security by applying it to the case of railway transport.

On a European level, for example, it is established the "Development and Management of Safety." This states that:

> Each managing authority in the infrastructure and each railway company is responsible for its own part of the system, and of its relative working safety, including the supply of material, the contracting of services for consumers, clients, connected workers and third parties.

To do this.

> The managing authorities of the infrastructure and the railway companies issue the regulations and, where required the necessary working rules

As might reasonably be expected the European legislator aims to "improve the interoperability of the service by bringing into line the regulatory structure of the member states." A clear "division of responsibility among interested parties" is shared out, and common principles are defined for "the management, the regulation and supervision of railway security."

In agreement with the safety directives, the EU Member States have to first guarantee the constant improvement in railway safety, keeping in mind the evolution of community rules and technical and scientific progress, giving priority to the prevention of serious accidents.

For this reason two subjects were introduced in 2004 who are responsible for railway safety, i.e., the Managing Authority for Railway Security and the Railway Company. These two subjects are "the only ones responsible for the safe working of the railway company and the control of risk." The two types of subjects are therefore obliged to set up the necessary measures of risk control and to establish systems of security management.

The European legislator then got down to indicating "who" is responsible (the subjects or the managing authorities responsible for the infrastructure and the railway company), the *object* under protection, i.e., the "what" (safety as concerns the pertinent part of the system), respectfully allowing the *responsible subjects* to choose and define the measures to be established (the "how").

To understand the motivation of such an operating method, we refer, for example, to the field of safety in the place of work.

Let us suppose that during the restructuring of a premises we decide to remove material containing asbestos rather that sealing it off (this is not an obligatory choice, but is entrusted to the company carrying out the work dealing with this type of material). Let us also suppose that the company doing this job has not correctly isolated off the area where this dismantling is to take place and that some dust has got loose (through air vents, stairways, lift shafts, etc.) and settled in parts of the building where people are regularly at work.

Should working people be exposed to such materials, the presence of which has been proven by correct measurement, their safely would naturally be endangered. In this case, the company carrying out the work would not be able to defend itself by stating that it is not responsible for the fact in itself because it is unpredictable by nature; neither could it count on the fact that it has not violated any legal disposition because there is no regulatory prescription in this connection which specifies how to carry out the work of sealing off the area.

The employer could not even make an appeal based on the fact that the law is inadequate, because it should, for example, specifically prescribe procedures for the closure of the plant or the sealing off (rather than the removal) of such materials.

The decision to evacuate the work place or to seal off the materials containing asbestos instead of removing them are assessments which need to be defined in the *work plan* that has been laid out and drawn up by the employer based on a necessary risk evaluation. Decisions about methodology (how) and the preventive measures to be set up are assigned to a *responsible subject* who, as he works in that particular sphere, is able to put them in act and carry them out in an adequate way from the point of view of techniques, technology and know-how.

From the example we have given, it should, therefore, be clear that the technician in this field needs to be able to distinguish the observation of the law and the regulations (the "what") from standard measures and methods (the "how") which are able to guarantee the protection of the *object* as imposed by the law.

The Organizational Accident Model as Applied to Collisions Between Aircraft Caused by an Incursion on a Runway

The Accident in Tenerife

In the accident in Tenerife Airport, the Pan Am airplane was following the KLM airplane entering the same runway and carrying out the indication given by the airports Air Traffic Control. The crews on the KLM were aware that an airplane was following them, but, despite the fact that there was no sight contact because of poor visibility, the captain—supported in this by radio communications that had been received incorrectly—thought that the airplane behind him had already cleared the runway. Therefore after having turned, he began take off operations.

Neither of the airplanes should have landed in the small airport of Los Rodeos, where the accident took place. Like all the aircraft in arrival at the international airport of Las Palmas (Gran Canaria) these two Jumbo Jets had been redirected to the small airport in Los Rodeos. In fact, on 27 March 1977 a bomb had exploded at 13:15 in a florist in the Las Palmas Airport terminal. Fifteen minutes before the explosion, the authorities had, however, received a warning by telephone and had managed to evacuate the terminal in time, so that only eight people had been injured. This decision had its effects not only on the passengers waiting for departure, but also on the great number of flights in arrival, many of which were at less than an hour's distance from the airport. For passenger safety all incoming air traffic to Las Palmas Airport was redirected to Los Rodeos, an airport on the small island of Tenerife, 70 km west of the Gran Canaria.

Los Rodeos was a regional airport that could not accommodate a great volume of traffic: it had only one runway and one main taxiway parallel to it and connected by small linking by-ways. The KLM flight landed there at 13:38 and the Pan Am Jumbo half an hour later, followed by a DC 8 and a Boeing 727. While the airport in the Gran Canaria was closed the redirected traffic was added to the local flights bringing the number of airplanes on the ground that day to a total of 11. It was necessary, because of these conditions, to use the taxiway as a parking place, where these large airplanes got in each other's way making it impossible for the aircraft to move along the ground normally. So it was that departing aircraft had to get ready for take-off by taxiing along the main runway, which is a rare procedure in commercial airports and known as *back-tracking* (taxiing in an inverse direction along the main runway). At 15:00 the bomb scare was over and the airport of Las Palmas was re-opened. After having filled up with fuel, and because it was at the head of the queue on the runway, the KLM flight contacted the control tower to receive authorization to taxi out. As all the linking by-ways were blocked by other waiting airplanes, authorization was given to this aircraft to enter the runway and go all along it to the end where it would turn 180° so that it would be ready for takeoff. At 16:32 while atmospheric conditions were worsening and visibility was falling, clearance was given to the Pan Am flight as well to taxi out behind the KLM. The Pan Am was told to go along the runway to exit number 3 and to turn off there

entering the parallel *taxiway*, thus freeing the main runway as soon as possible for the KLM's take off.

Initially the pilots on the Pan Am did not understand whether the control tower had told them to turn off at Exit 1 or Exit 3: it was not clear whether the air traffic controller had said "first" or "third." The crew asked for clarification and the control tower answered categorically: "The third, Sirs. One, two, three – the third!"

However, the pilots of the Pan Am thought that Exit 3 was too complicated: they would have to turn 135° to the left and then again 135° to the right, risking that the wheels on the airplane's landing gear might go off the runway into the grass at its edge, where the ground would not have been able to bear the weight of the Jumbo Jet. The registrations of the plane's flight recorder indicate that the pilots disobeyed the orders given by the control tower and passed Exit 3, then attempting enter the fourth, which seemed simpler to them (it was a turn of only 45°).

In the meantime, the KLM had arrived to the end of the take-off runway, made the 180° turn and was ready to take off.

The captain of the KLM flight moved the engines' thrust levers forward: this is standard procedure to be effected before taking off and is called "*spin up*" to check that all four engines are responding correctly before starting take-off. The KLM co-pilot then contacted the control tower to obtain clearance for take-off. At this point the control tower gave clearance instructions and the route for the airport in Las Palmas.

In thick fog, the KLM could not see the Pan Am which was taxiing along in the opposite direction in front, just as the Pan Am could not see the KLM. The control tower could not see either of the two airplanes because the airport did not have surface movement radar (which was in fact rare technology in those days seeing as it had only recently been invented).

The KLM co-pilot repeated the instruction he had just received, saying: "We are now taking off," and the control tower replied "Ok, stand by for take-off. I will call you."

However, because of serious interference on the radio, caused by radio contact that was being made at the exact same time by the Pan Am, the words from the control tower arrived to the KLM in the following form: "Ok . . . for take-off."

Communications of this type, which were usual practice at that time, would be considered highly dangerous by modern standards: the use of the word "take-off" before the real take-off itself in addition to a non-standard acceptance form like "Ok" can give way to misunderstandings and are the possible beginning of a disaster.

Convinced that they had received clearance for take-off, the pilots of the KLM released the brakes and gave full thrust to the engines. In that precise moment the Pan Am warned the control tower that it was still on the runway, but this message went unheard in the KLM because of interference on the radio.

In the meantime visibility had shortened to 150 m and a light rain was falling. When the KLM saw the outline of the Pan Am at a couple of 100 m it tried to anticipate take-off: it just about managed to get off the ground, but the landing gear and the bottom part of the fuselage hit the Pan Am, cutting it open.

The Pan Am aircraft immediately caught fire and, after having flown for about 100 m, the KLM stalled because pieces of the Pan Am's wreckage had been sucked into its engines. It therefore lost height and crashed down on the runway, coming to a stop at about 300 m on, immediately catching fire.

As a consequence of this disaster, there were a number of changes made to the regulations used in managing air traffic. Aviation Authorities introduced the obligation to use standard phrases in communications between aircraft and the control tower so as to avoid any possible misunderstandings.

Non-conventional expressions were prohibited and it became obligatory to repeat word by word any order that had just been received when communications were particularly important so as to make sure they had been correctly understood. Moreover, the use of the term "*take-off*" was restricted only to clearance for the real maneuver itself: in any other context the general term utilized today is "*departure*," which we can all hear travelling on modern airplanes when the captain tells is cabin crew to get ready for that event: *departure* is used in all cabin communications which take place before effective clearance has been given for "take-off" from the control tower.

A great deal of care is also given to a perfect knowledge of the English language in radio communications on the part the pilots and the personnel in control towers.

A new airport was opened in Tenerife in 1978, built on the other side of the island in an area that was not subject to banks of fog: this new airport has gradually substituted the one in Los Rodeos.

Today the airport of Los Rodeos is equipped with surface movement radar and it is mainly used for local flights.

The Accident in Los Angeles

On 1 February 1991 Flight USAir 1493, identifying a scheduled US Airways flight between the cities of Syracuse and San Francisco, collided with SkyWest Flight 5569 during landing in the International Airport of Los Angeles. The accident was caused by the distraction of the local flight controller who gave clearance for the take-off of a little SkyWest Metroliner on the same runway on which a USAir Boeing 737 was landing. Twenty-eight people on board the B737 and all twelve of those on the Metroliner lost their lives in the accident.

The local controller who authorized the two airplanes to use the same runway admitted his responsibility in front of the investigators of the US *National Transportation Safety Board* (NTSB), the American government body for inquiries into accidents in the transport sector. The Air Traffic Controller immediately told his supervisor that the USAir Boeing had most probably collided with another aircraft, adding in his own partial defense that from his position he could not see a small aircraft like the Metroliner because of the lights that were reflecting on the window panes of the control tower and the near invisibility of the navigation lights set on the back of the Metroliner's wings. From the height of the control tower these

navigation lights were practically "drowned out" by the three brighter lines of lights along the edge of the landing runway which was also used for take-off. The Metroliner's lights were on while the Boeing 737 was coming dangerously near from overhead, but they were not stroboscopic, which the pilots of the Boeing might have seen from the air, because at that time there was no regulation making it obligatory for strobes to be turned on during taxiing.[12]

Using a helicopter, the investigators were able to reconstruct the Boeing's effective visibility condition during landing.

The investigators positioned themselves at the altitude limit from which the captain of the USAir Boeing 737 in arrival would still have been able to interrupt the plane's landing, while at the same time they placed an identical Metroliner on the runway (at the same time of night) with all its navigational lights on except the strobe: and effectively from that arrival position the investigators were not able to make out the Metroliner on the runway. Even if it was present on the runway with all its lights on, the Metroliner was still practically invisible at distance and altitude from it would still have been possible to have made a last-ditch attempt to interrupt the Boeing's landing maneuvers.

They also verified what the air traffic controller had said about disturbances to his field of vision caused by a blinding light when he had tried to see with his own eyes whether the runway really was clear or not. Once again the investigators had to confirm that the sight from the control tower was in fact disturbed by floodlights that had been placed at the same height as its own windows.

The investigators also found that the surface movement radar terminal was not working although in the days running up to the accident Air Traffic Control authorities had repeatedly asked for repairs to be carried out with the highest priority. This request had gone unheard.

For these reasons, the commission of inquiry of the NTSB concluded that as they drew near to the airport the pilots of the Boeing 737 could not see the Metroliner because its navigation lights got mixed up with the other lights on the runway and the controller could not correct his error as his last eyesight check was blinded by the low visibility anybody could have from the control tower to the place on the runway where the Metroliner was positioned.

The commission also concluded the airport was to be considered responsible for the fact that the management of the runways had been entrusted totally to the local air traffic controller because the surface movement radar was out of order, and for the problem that, because of the heavy traffic, both landings and take-offs were being cleared on each of the four runways.

One of the final recommendations that the NTSB eventually made was to diversify the use of runways so as not to have landings and take-offs on the same track. This came into effect only after 19 August 2004 when another accident

[12] Since then, from indication given by the US NTSB, the commission of inquiry, it has become obligatory to use strobe lights even during taxiing.

almost occurred: a Boeing 747 which was landing on runway 24L risked colliding with a Boeing 737 that was waiting on the same runway.

From then on the external runways of the Airport of Los Angeles are used only for landings, while the internal ones are used for taking off.

Lately, experiments have been carried out for the first time with innovative luminous signs that automatically recognize the fact that an aircraft is drawing near to the runway—these automatically light up when another airplane is coming near the runway, either landing or taking off. Without having been any communications on board from Air Traffic control, an airplane that is approaching on a by-pass taxiway sees traces light up along the ground in front of it: this tells the captain that the runway ahead is occupied with an aircraft that is landing or taking off.

Along with the surface movement radar this system gives greater solidity to the protection network against mistakes involving more than one aircraft on a single runway, something that has in the last few years become far too common in Los Angeles Airport and other airports with heavy traffic.

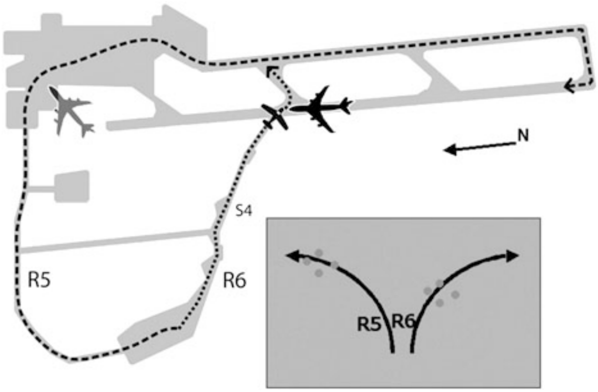
The Accident in Linate Airport, Milan

Figure 5.1 is a diagram of the airplane accident in Linate. During take-off an SAS flight collided with a small Cessna. The disaster took place because as the result of an error the small aircraft had taken the R6 by-pass taxiway which ran along the main runway instead of moving correctly along the R5 by-pass, which would have taken it round to the end of the runway behind the SAS (cf. Fig. 5.1).

The first communication problem between the Cessna and the control tower took place at 8:05: the tower gives directions to the Cessna telling it to take by-pass R5. The Cessna responds correctly R5, neglecting however to repeat some of the words and arrives at the fork between R5 and R6 (cf. Fig. 5.1), where the letters of the road signs on the ground are difficult to read because they have faded in time and are broken up and below international standards. The Cessna arrives at the fork and takes the R6, the by-way on the right instead of the R5, the one on the left. The worn out letters on the ground are difficult to read in the conditions of low visibility on that day. The lights on the R6 by-way, the wrong one, are lit up and instantly visible at a distance of 80 m, while those on the R5 are further off and not immediately visible. It is possible to imagine that the pilots were influenced by this aspect, persuaded by the fog in this mistaken conviction.

The second communication problem came about more or less half-way down the by-way, at the point indicated S4 in the diagram. It is the second communication between the tower and the Cessna and maybe the most problematic of all their exchange of messages. The Cessna communicates that it is approaching point S4, the tower asks doubtfully for confirmation and the Cessna replies: ‘I am approaching runway Sierra Four, i.e., the take-off runway, and the tower replies: “OK, stop at the stop bar. I’ll get back to you” (meaning the stop line of the R5 by-way). The Cessna replies: “I’ll hold position". There have been many

Fig. 5.1 Layout of Linate accident



interpretation used of this term hold position. It is reasonable to say that the expression approaching runway used by the pilot could only have been said by a plane on the R6 by-way because as is evident from Fig. 5.1 only by-way R5 goes round the runway; position S4 is indicated only on the R6 by-way, but it is nowhere present on the air traffic controllers' maps or even on that of the pilots: it is an indication that belongs to a sign system that has for some years fallen into disuse, and the controllers in the tower no longer even remember it. In the last communication neither of the two sides would seem to be listening to the other: each of the subjects means different things even if they are using the same words. The tower gives indications to continue taxiing along the main runway, meaning by this the zone managed by the SEA (the company that manages the airport system) i.e., the parking area, and gives indications to follow the Alfa line (on the main maneuvering area). The Cessna replies correctly that it is going in that direction, receiving confirmation from the control tower with yet another read back. Yet in fact, in all these totally misleading communications the Cessna is referring to the R6 by-way and the control tower to the R5 by-way.

The Cessna enters the runway during the SAS's take-off and the impact occurs. The SAS then continues its motion and ends up by slamming into the luggage holding building.

The Three Levels of Failure in the Accident in Linate

To a depth analysis of the failures at the airport of Linate, a model of an organizational nature, is correct approach as it is capable to set out: (a) the so called *active failures* on level one, i.e., mistakes made by people working in the front line, "the weakest link of the chain"; (b) the so called organizational failures on level 2 *organizational failures* connected with factors inherent with the management system of an airport this case and which, therefore have to do with the defense of the system (the signs, the technology in use and so on); and at the third level, the so

called inter-organizational failures, which involve those bodies who have to do with the management of safety (in this case the safety of air traffic).

Each of these levels is embedded in the other, and so active failures are promoted by organizational failures which are facilitated in their turn by inter-organizational failures.[13]

The Linate accident has been deeply analyses by an organizational accident approach by investigators. Actually two phases are recognizable in this accident,[14] the first of which lasts 4 min 38 s, i.e., the period between the moment of the first communication between the Cessna and the control tower and the moment of impact. This phase involves mainly active failures, but the accident itself was built up over a longer time span, years and years during which there were organizational and inter-organizational failures connected with management bodies. As regards the first level, involving active failures, it is clear that the Cessna took the wrong by-way entering the R6 instead of the R5. There were failures in communications, and low visibility procedures were not applied although these were necessary in the conditions of fog, more so if you consider the fact that there was no surface movement radar or other instruments that could fill in for it.

There were a number of organizational failures in this case. There were failures in the security system, like the absence of an anti-intrusion bar between the R6 by-way and the runway[15] and the absence of (sound or flashing light) indicators on the air traffic controllers' console, which would give a warning about a possible unauthorized entrance on the runway.[16]

Investigators analyzed the accident in Linate underlining both failures because of bad communications and the non-application of cautionary safety procedures in low visibility (which become even more important considering the fact that there was no surface movement radar) including problems deriving from the high task loads of the pilots and air traffic controllers working as we have seen in situations which fall short on technology and instruments. Looking carefully through the regulations to protect against and prevent the impact of active-type errors, it emerged the use made of signs was totally inadequate. The indications R5 and R6 were not clearly visible at all and this had particular relevance in the accident because when they had missed the initial display of such signals, and because the sign R6 was never repeated, the pilots had no chance to verify their position at any other point along the by-way ahead.

If you go today onto the same by-way, you can see more or less 20 signals, on signs or along the ground and at least ten of these contain the indication R6. Today it would not be possible for the pilots to taxi forwards in the mistaken conviction that they were on the right by-way even in the absence of surface movement radar

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[13] M. Catino, *op.cit.*, 2006.

[14] M. Catino, op.cit., 2006.

[15] There was a bar, in fact, but it had been disactivated years before.

[16] Here again, it is interesting to note that an anti-intrusion indicator had been present on the old model of console used in the control tower of Linate.

because the correct indications are repeated over and over again. But that day this clarity was missing.

Another organizational failure that could be mentioned is the habit of using as little as possible a *follow me* vehicle to indicate the right way to take when there is fog simply because its employment involves delay in take-off times. Pilots themselves frequently insist that they do not want to use them, falling back on the fact that no authorization body imposes their utilization.[17]

Lastly, a most controversial and most important type of analysis, the inter-organizational, level, was conducted.[18] As came out even during the trial, roles and competences were not clear in connection with security.

Seeing as there was no real co-ordination, the operators involved tended to pass on responsibilities in a dangerous game of passing the buck. All this in a context that was not clear. The conflict between different supervisory concepts put the pilots and the air traffic controllers in a position where they had to decide between rules for safety and rules for efficiency. And when a single operator found himself having to choose between two totally different regulatory worlds, it became easier to make a mistake. The pressures adopted to achieve a higher level of efficiency were not integrated with the need for safety: that day the airport of Linate was just not equipped to function in an adequate way with the number of airplanes present.[19] The level of individual failures is always to be placed inside an organizational level that can be inserted in its turn on an inter-organizational level.[20] So for Linate once again we are talking about an organizational accident—and we can no longer think about it as the result of human error. The accident had been incubating for years and years and Linate was a system that could induce error.

It is not only that the system was not able to prevent mistakes: the mistake itself had been given consent and constructed by that system: once a mistake had been made, the system was not able to contain the consequences.

After this accident surface movement radar was installed in Linate.

Conclusions

By habit the analysis of an accident is always excessively simplified, at least in the very first phase, re-conducting it to a mistake made by the last active subject, the *front-liner* in the chain.

This frequently happens when the person who is conducting the analysis has never really had any experience of the complexity of an organizational accident: in the presence of a disaster arising from human error it is always essential to verify whether the necessary "protective networks" were active.

(continued)

[17] M. Catino, *op.cit.*, 2006.

[18] M. Catino, op.cit., 2006.

[19] M. Catino, *op.cit.*, 2006.

[20] M. Catino, *op.cit.*, 2006.

These are dispositions set up to avoid the circumstance that a cognitive error or an error of perception can provoke consequences that are so disastrous.

If we were to suppose that in today's world our safety should depend on the choices made by one man, who, because he is merely a man, is of course subject to failure, then it is probable that no one would board an airplane or get on a train or a bus or go to work in a factory.

This is something we believe, a feeling that we all have, but the elaboration of this simple concept has been refined today thanks to our growing culture in the subject of safety in human activities. We now know that as regards human and industrial activities, security needs to be activated and constantly improved based on the evolution of regulations.

Failures in complex systems are no longer reduced in their interpretation as errors of "the last link in the chain": these failures are treated nowadays with an approach that aims to qualify the active last man's error on one side, and also to understand why this error has been so decisive in provoking disastrous effects.

Furthermore, we always ask ourselves if such an error can be described as an isolated case or if it does not, rather, emerge after a long phase of incubation during which the sufficient conditions were created for the occurrence of an error to which no adequate remedy had been created.

Repeated failures get stratified each time the recurring operation takes place without serious consequences. We might be aware of the potential criticality, but all temporary successes satisfy the organizational system: a limited lack of success makes people think that such things are merely constraining a system that is not yet "expert" or "mature" in its own field. These constraints, some people believe today, are crushing the system and need to be eliminated.[21]

This goes on until one day the system is as tight as a violin string and ready to break.[22]

Literature that goes into an analysis of failures (post-accidental analysis) has *de facto* abandoned both the concept of the technological/procedural (or regulatory) failure and that based on an identification of the human factor: today any serious analysis must embrace them both.

As it is logical to expect, accidents have both a technical and a human component, but failures are always stratified on three interconnected levels.

Or more than interconnected, we could say that they include each other.

(continued)

[21] S. Nashef, "What is a near miss?," *The Lancet,* 361, pp. 180–181, 2003.

[22] This was at the heart of the severe analysis that Feynman brought in front of the Government Inquiry into the disaster of the Challenger.

– Active failures or "last link of the chain" failures which come into play, setting off the first event;
– Organizational failures, in which the protection network has not been correctly disposed so as to mitigate the risk and impacts of an active failure;
– Failures at an inter-organizational level which allow the "organizational system" to go astray moving progressively to a distance from the principles of research, guarantee and continuous improvement in safety.

All this often happens because there is too much confidence that, all things considered, the system can tolerate overloading in the name of greater productivity and efficiency. As was the case in the decision not to create a negative impact on the growing airport traffic by activating restrictive security protocols, at least until the surface movement radar in Los Angeles and Linate had been repaired or by safely using an emergency airport equipped with surface radar for management of such complex traffic in low-visibility condition, as was the case for the small local Los Rodeos airport in Tenerife.

In a nutshell: the trigger event starts from an error: the conditions that make it come about that the error is transformed into a disaster are created long before. To pinpoint the predictable or avoidable contents of the event it is necessary to carry out a careful analysis of all those causal factors that culminate in the *top event*. This is what we will do in Chap. 6 in agreement with the inspiration of the whole of modern engineering: efficiency in the respect for the safety of human beings.

Chapter 6
Multi-Level SEA Analysis for Tracing Criminal Responsibility in Organizational Accidents

Introduction

Now we are ready to elaborate a complete SEA analysis with its conduct level, divided and structured on three sub-levels: an “active” or front line sub-level, an “organizational” or “prescriptive” sub-level and the last “inter-organizational” or “control” sub-level. These three sub-levels fit into the three failure models that we find in the literature on organizational accidents.

Thus we have:

– The “active” conduct sub-level, which is to be understood as the complex of actions and omissions attributable to frontline personnel;
– The sub-level of conduct on the “organizational” plane, to be understood as the complex of actions or omissions (here we are generally talking about omissions); this sublevel determines the failure of the “protection network,” which should have stopped frontline-type errors from degenerating;
– The sub-level of conduct on the “inter-organizational” plane, to be understood as the complex of actions or omissions (here we are generally talking about omissions) which determine the failure of the bureaucratic-regulatory and/or the controlling or executive system. This sublevel should have been monitoring the system to make sure it was well-protected from dangerous deviations which often have a proactive role in the progressive reduction in safety of the activities carried out.

Figure 6.1 is a general diagram which is arrived at by organizing the level of conduct as described above.

Three different types of conduct influence (and are therefore necessary conditions for), the evolution of event E1. To determine whether one type of conduct is a necessary condition for event E1, a procedure called “mental elimination” is applied and this is typical of counterfactual reasoning, of the type “if not A, then not B,” that is to say:

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DOI 10.1007/978-3-662-47898-1_6

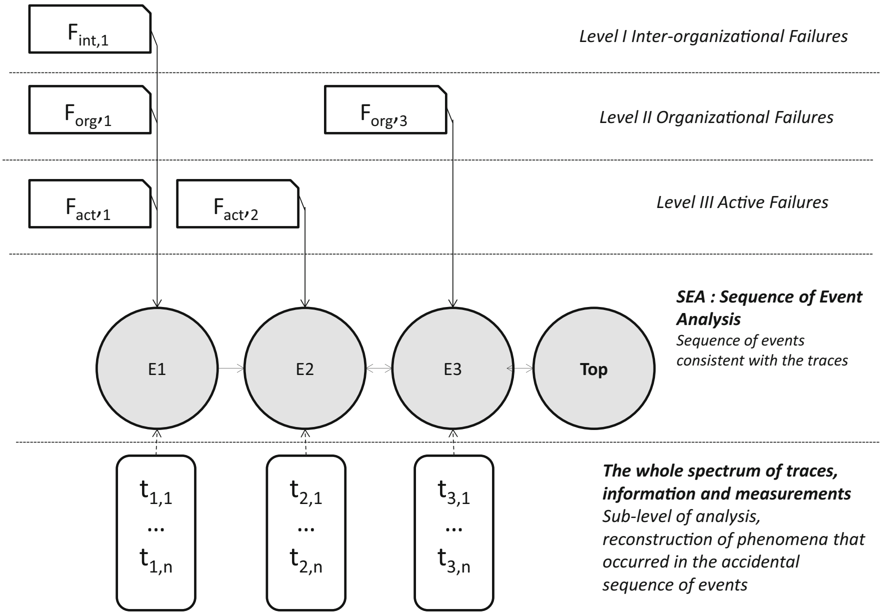

Fig. 6.1 An example diagram of the multilevel SEA method for tracing responsibility in an industrial accident

- If conduct Fact-1' had not taken place then there would not have been the sufficient conditions for the occurrence of event E1
- If conduct Forg-1' had not taken place then there would not have been the sufficient conditions for the occurrence of event E1
- If conduct Fint-1' had not taken place then there would not have been the sufficient conditions for the occurrence of event E1

At the end of this mental elimination test we arrive at the conclusion that the three types of conduct Fact-1', Forg-1', and Fint-1, belonging to three different levels of the organization (active, organizational and inter-organizational) are all necessary for event E1: not only that, it is enough for one of them to be absent to stop the event E1 from happening.

In other words, each of the three types of behavior is a necessary condition for event E1 to take place, and all three of them together determine the sufficient circumstances for the occurrence of E1.

The first conclusion that we can reach is that, from the equivalence of causes, all three types of conduct are the cause of event E1.

Let us now move on to the events E2 and E3, putting them in relation, first, to their preceding event (obviously E1 is E2's preceding event, while E2 is E3's predecessor) and second to the conduct which influences them directly (the event E2 is influenced by Fact-1', while E3 is influenced only by Forg-3'). Notice also that events E1 and E2 are connected with a mono-directional arrow, while in E3 and E2

the connecting arrow is bi-directional. This indicates that event E2 does necessarily follow E1, as opposed to what happens for event E3, which unavoidably follows E2. Lastly, let us suppose for the sake of simplicity that the damaging event becomes concrete only with the occurrence of the final top event following event E3.

The damaging top event has been caused by failures that are identifiable in all three different conduct levels. Specifically here, failure Forg-3 was not able to limit the frontliner's active error Fact-2, which is directly responsible in its turn for the key event E2 from which both the event E3 and the (destructive) top event inevitably originate. Although errors Fact-1, Forg-1 and Fint-1 were made (and, therefore involve three different levels of the organization) and have, in fact, provoked the initial E1 event, they cannot be considered sufficient, but only necessary for the uncontrolled evolution that carried the system on from event E2 to the final damaging event. The set of Fact-1, Forg-1 and Fint-1 in conjunction with the active error Fact-2 and with the inadequate "barrier" given by the bad planning of the system Forg-3 is to be considered the sufficient condition (the cause) of the top event.

A Practical Application: The Case of the Accident in Tenerife

We can have another glance at a concrete example to look beyond the general diagram we have proposed and focus on how useful multilevel SEA really in tracing responsibility.

In Chap. 5 we described the tragic accident which took place at the airport in Tenerife, when two airplanes collided as one of the two was taking off because it found the other on its path coming in the opposite direction.

There can be no doubt that, among the various key events that make up this particular chain, the most important are the instants when the captain of the KLM flight "turned on the engines" and "released the brakes" and when the Pan Am "missed turning into by-way 3": these are three events that preceded the collision or top event in time.

In this case, the sequence of events needs to be considered in a double way because the system that we are studying includes two aircraft which are acting separately: each of them has its own story line from which to construct the key events.

Looking back over the causal succession identified by the commission of inquiry, we know that the Pan Am jumped the entrance to by-way 3 just as the KLM released the brakes, immediately after starting take-off procedures.

The events "KLM releases the brakes" and "Pan Am jumps the entrance to by-way 3" are the two events of "no return," those that brought the "system" of the two aircraft to the inevitable final collision (cf. Fig. 6.2).

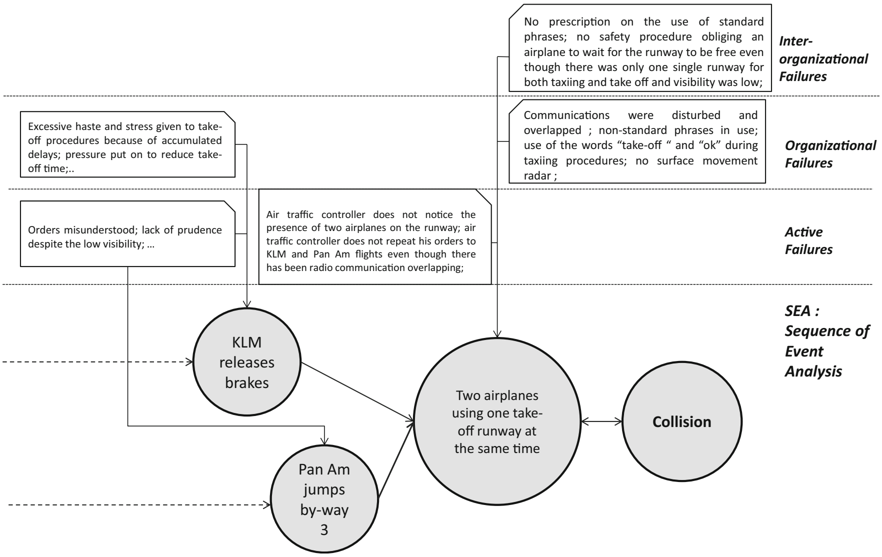

Fig. 6.2 Example of an (a posteriori) multi-level SEA reconstruction illustrating the final events taking place during the accident at Tenerife in 1977. The diagram does not show the level related to the "traces" that give consistency to the accidental sequence of events displayed; the reconstruction is based on information available today in the official documents of the inquiry into the accident

Making an in-depth analysis of the failures that brought the KLM flight to the point of erroneously getting underway with take-off when the Pan Am was still on the runway, you come across the incomprehensible radio communications with the control tower.

Some phrases were badly received and badly interpreted by the captain of the KLM. The KLM flight captain's failure (frontliner error) consisted in his mistaken interpretation of a phrase communicated by the air traffic controller in the tower (another mistake by a frontliner). However, these two active failures are contained in an equally evident organizational failure which was not equipped at that time with a protection network: the control tower had not used standard phrases.

To tell the truth standard phrases were not yet a prescribed measure at that time, and that brings us to the identification of a further circumscription of the frontliner's mistake inside yet another failure. This time we are talking about an inter-organizational failure: until that day none of the regulatory bodies had ever considered the problem of reducing the risks connected with difficulties in comprehension of the English language (regarding crews and airport control personnel who were not native English speakers). The least that can be said is that the problem should have been put on the agenda, considering the extraordinary growth of commercial traffic from all over the world which had been registered at the beginning of the 1970s.

Seeing as visibility was lower and surface movement radar was not available as a further protection network, the air traffic controllers made another active mistake when they failed to ascertain whether their orders had been thoroughly understood by the KLM captain.

In the same way, there is the evident active failure made by the pilots of the Pan Am when they decided arbitrarily (despite orders given by the control tower) to pass by-way 3 and continue along the take-off runway to reach the farther but more convenient by-way 4.

On the organizational level again there was the failure because of the airport air traffic control authorities who authorized the back-up use of a take-off runway as a taxiway.

It is true, of course that in this particular case, according to the reconstruction made, they did not really have much alternative because of the presence of aircraft parked on the taxiway parallel to the one and only runway for landing and take-off in the small airport of Tenerife.

Yet it is also equally clear that the airport authorities could have kept to a higher level of security, precisely to avoid carrying out such a dangerous procedure in the middle of thick fog and without the assistance of surface movement radar.

They could quite simply have ignored the pressure the pilots of the parked planes were putting on them—who were themselves coming under pressure from their passengers on board because of the enormous delays that had been created. Either that, or they could have given orders that each plane next in line after the one that was involved in the process of taxiing out had simply to wait immobile where it was until the aircraft in front had completed take-off.

Brief Notes About the Origin of Sequence of Events

Multi-level SEA borrows from the "Ishikawa diagram" or "cause effect diagram" (cf. Fig. 6.3), which is also called the "fishbone." Mobely numbers this diagram among the general techniques used in the analysis of the causes of an accident according to the typical approach of Failure Analysis.

The classical Ishikawa diagram was re-elaborated of the basis of the re-interpretation formulated by Reason in connection with the conditions which determine unintentional situations capable of resulting in an accident (cf. Fig. 6.4)

Using a "four stage" process, Reason comes to grips with the theory of human error produced in a "favorable environment" (cf. also the connected diagram "The Classification of Errors According to Reason").

Reason uses a systematic approach to the study of error, also called the theory of latent errors, which we have already discussed in the examples of accidents in Chap. 5.

Accidents, above all the most serious ones that turn into disasters, are only the tip of the iceberg. For every single accident that has actually occurred, there might have been many others that were "close calls" and did not take place only because

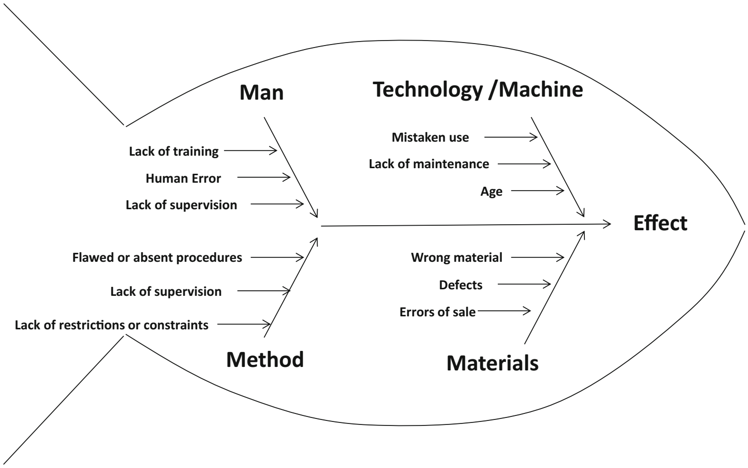

Fig. 6.3 General schematic view of Ishikawa's cause-effect diagram

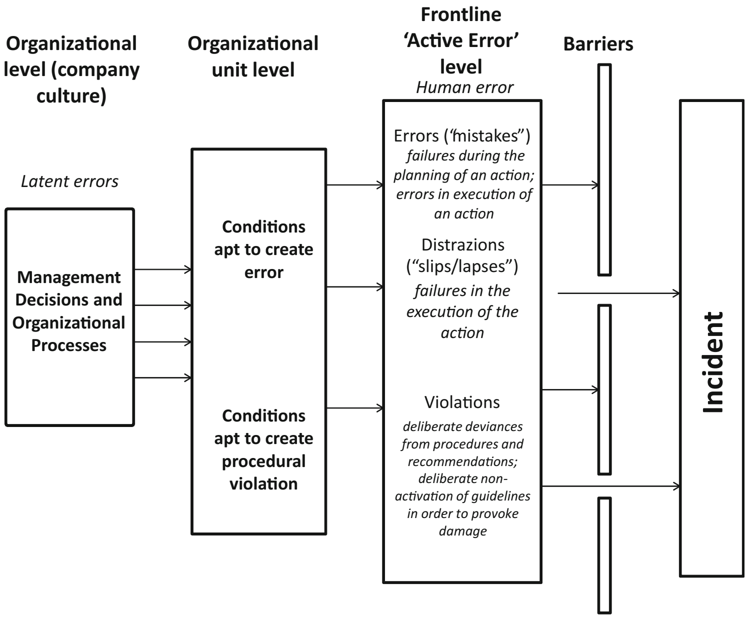

Fig. 6.4 Error diagram according to J. T. Reason: an error is the effect of a "four stage" process not reduced by the barriers put in place as protection

an operator of a control system stopped them from happening: we are talking about so-called near miss events from this systematic vision comes the idea that the occurrence of an accident is the result of a connected series of events that have jumped all the defenses activated to stop them.

The Classification of Errors According to J. T. Reason

In the area of the theories that have been developed for the study of error, that regarding human error proposes a classification of human behavior in three different types:

- Skill-based behavior: these are types of behavior that are automatic to a given situation. A stimulus is given to an individual and he reacts mechanically to this without thinking about problems connected with the interpretation of the system itself. Ability of this nature is developed after the stimulus has been given repeatedly, and always in the same way. It is the type of behavior that can be found in routine situations.
- Rule-based behavior: certain types of behavior are activated by prescribed rules. Such behavior has been defined as the type of conduct that is considered to be most correct in a particular circumstance. The problem that the individual must face is how to find the right regulation for each specific situation, in respect of a causal-type mental model.
- Knowledge-based behavior: this is a type of behavior put into use when we find ourselves facing an unknown situation and have to activate a plan to overcome it. Such situations require the greatest degree of understanding and the activation of a series of mental processes that leads from symbols to the elaboration of a plan allowing us to reach our aims.

These three types of conduct can be acquired in sequence: there are no skill-based types of behavior that are inborn, but they all derive from practical know-how in situations which from the outset required the use of understanding and the ability to resolve problems. It follows that any conduct based on practical knowledge was of a rule-based type before it became automatic, and even before that it was knowledge-based. The error can stem from each level of conduct, but the causes are different: a mistaken interpretation of the stimulus at the skill-based level; the choice of an inadequate regulation in rule-based conduct; the planning of unsuitable strategies to face the specific aims of the situation on a knowledge-based level.

Based on the model proposed by Rasmussen, Reason distinguishes between errors in execution and actions carried out according to intention, thus outlining three different types of error:

- Errors of execution that come about in the level of ability (slips). This category classifies all those actions that are executed in a way that is different from how they were planned, i.e., the subject knows how he should carry out his task, but he does not do so or unintentionally does it in an incorrect way (e.g., the patient tells the nurse about his or her allergy but the nurse forgets to tell the doctor).
- Errors of execution provoked by memory failure (lapses). In these cases actions lead to results that are different from what was expected because of memory failure. As distinct from slips, lapses are not directly observable.
- Errors not made during the practical execution of the action (mistakes). Here we are talking about previous errors that have developed during the planning

processes of a strategy: the target is not reached because the tactics and the means used do not allow that particular aim to be reached. Such errors can be of two types:

– Rule-based: a rule or procedure has been chosen and applied that does not lead to the achievement of that particular aim;
– Knowledge-based: these are errors that have to do with understanding; in some cases a subject's knowledge can be so superficial that it actually encourages undertaking paths of action that do not permit the achievement of the target that has been fixed. In such circumstances, the plan itself is wrong even if the actions carried out were executed in the right way.

Violations fall into a separate category. By violations we mean all those actions that are in fact carried out even if they are formally prohibited by the rules, directives, etc. It can frequently happen that the directors of a company impose security norms that enter into conflict with the correct execution of the work to be done.

Management of Risk Using Root Case Analysis

Root Cause Failure Analysis (or RCFA) is the principle instrument today that can be applied to the analysis phase in the process of risk[1] management.[2] In fact, this phase can itself be considered a process: the input is represented by the information collected during the phase of risk identification, for example by indicating events of interest (incident reporting), while the output are the indications given as regards treatment reserved for the risks observed. Intermediate activities have an added value and consist in the creation of operations that lead to the identification of the reasons why an event has come about and to the evaluation of the extent to which such reasons can be resolved or what actions need to be taken for their management and the construction of a realistic agenda to prevent the repetition of the accident.

RCFA is a structured inquiry that aims to identify the real cause of a problem and the steps that need to be taken to eliminate it (Anderson, Fagerhaug, 2001). It is, therefore the most frequently used instrument for the analysis of risk in all fields where a risk management system is in operation. The analysis of in-depth causes is a method applied to the study of the causal factors in an adverse event, or, in general, an accident, which is based on an organizational conception of error. This

[1] The term risk indicates the relation between the probability that a specific occurrence takes place and the seriousness of its possible consequences. It studies the prospect that something might happen or that a danger can become real and have an impact on the aims that have been set up. It is measured in terms of consequences and probabilities. Risk assessment is the entire process of analysis, evaluation, the choices made and how to treat and monitor the risk.

[2] Risk management is built up from the culture, the structure and the processes that attempt to manage negative effects and improvement opportunities in the best possible way.

type of analysis, in fact, is not limited to pinpointing the mistake or the shortcomings that are in close proximity to the occurrence, but aims to analyze the entire process that that has given rise to the event itself. The main target of this methodology is to arrive at an in-depth understanding of what has happened, why it has happened and what can or must be done to make sure that it does not occur again.

In this sense, the root cause means the most basic cause that can reasonably be identified and which can be controlled by the management (Paradies, Bussch 1988).

Conclusions

The principle target of multi-level SEA analysis is to assist the lawyer, the public prosecutor or the judge in the delicate phase of "tracing responsibility" because, in agreement with the ideas put forward by Reason, it aims to identify and profile responsibility.

These responsibilities are determined based on both the frontliner's conduct, which have brought about one or more of the active errors, and also by considering all the other failures, often connected with omission, which are linked to the regulatory phases, organization, monitoring, checking and controlling.

We do not only consider in other words "the weakest link of the chain" but we also examine the actions or omissions of all the other actors who should have planned and set up suitable "barriers of protection" able to contain and reduce the danger created by the active error.

Widening out the various different causes of an accident on three diverse levels of failure is a step which objectively needs to be taken, in particular when the accident gives rise to a disaster. This is in line with the most modern understanding of risk management and is based on the elimination and the reduction of risk by carrying out careful studies of the system, its flaws, the dangers deriving from the man—machine or man—organization interfaces.

If it is true that pinpointing responsibility in the criminal sphere is not something that should aim merely to punish or to be connected with payment of damages, then the identification of the causal link been conduct and event must always be sought after by moving up and down the three "levels of behavior."

Chapter 7
The Sequence of Events Assisted by Computer Graphics: Two Case Studies

Introduction

Every complex industrial accident needs to be treated with the very same methodological approach that is normally used by the investigators when they have to reconstruct a crime, for example, a violent case of homicide. It is common knowledge even to non-experts that every crime scene is a mine of possible information which, when it is carefully interpreted, gives precious aid to the investigator in the difficult task of reconstructing the "dynamics" of the crime. If, for example, the investigator starts out by examining the particular shape of the wounds on the victim's body, he or she could come up with some idea of the type of weapon that inflicted the death blow. At the same time, from a study of the prints left on the floor by the murderer's shoes, a number of hypotheses could be made about his or her build or physique. For these very reasons the investigators carry out measurements, trying to "freeze" the relative positions of the surrounding objects and the body of the victim, gathering organic traces and taking fingerprints. Using techniques that are totally in accordance with Anglo-Saxon countries, for example, it is possible to set out from the examination of traces of blood on surface elements to formulate hypotheses about the position of the source that was bleeding and sometimes also the way in which the death blow or blows were inflicted, how much force was used

This chapter was written thanks to the important contribution and to the material made available by Tiziana Pedonese (Viareggio, 1969) and Salvatore Valese (Napoli, 1983). Tiziana Pedonese is an attorney at the Court of Lucca, Tuscany and as such she is involved as the representative of various parties bringing civil actions in the criminal hearings connected with the Viareggio railway disaster. In the same court, she also defended the accused whose case study is treated in this chapter under the heading "The Strange Case of Mr. J." Attorney Tiziana Pedonese defended the accused in this case by making use of the SEA technique, assisted by 3D graphics created by Salvatore Valese. All the 3D models and the animated 3D graphics presented in this chapter and discussed in the Court of Lucca were created thanks to the invaluable, irreplaceable work of Salvatore Valese, who is an expert in 3D graphic animation for the creation of static and dynamic scenes made for various areas of interest, including the courts.

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and whether the act is potentially ascribable to a single individual of a certain physique or sex.[1] And so it could go on. Any investigator making an inquiry into the reconstruction of the dynamics of a crime starts off, therefore, from a detailed **interpretation** of the **traces** present on the scene. The investigator gathers as much of these as possible is the first preparatory step towards the success of the subsequent phase, which consists in formulating the **hypotheses of reconstruction** concerning the dynamics of the accident. A critical analysis of the hypotheses the investigator can formulate shall be linked with the interpretation of the traces. This is a crucial phase of the inquiry because it forces the investigator to move forwards by carrying out a rigorous *screening* of those hypotheses that seem in any way implausible as they are not effectively capable of explaining the presence of all the traces that have previously been identified and catalogued. Here we are dealing with the need to eliminate the hypotheses of reconstruction that have turned out to be *inconsistent* with the traces. This verification phase is often conducted by questioning any possible suspects, by using an "empirical verification"[2] to reconstruct the sequence of movements that have hypothetically been made based on the traces present on the crime scene or also, in some cases, using virtual techniques to reconstruct the scene of the accident and the relative movements of the body.

[1] *Bloodstain Pattern Analysis* (BPA) allows you to trace the origin of bloodstains using the "projection mechanism" of liquids after they have impacted against a surface. By selecting some of the stains that are present on the scene it is possible to track those that have a unique *pattern*, i.e., a group of stains produced in a single origin in time. Having selected the "projection" *patterns*, it is possible to identify the size and morphology of some of the stains belonging to this group: the impact angle of the drop on the wall is calculated on this basis and thus, by working backwards, the possible impact trajectory. From where a number of trajectories intersect you can, with all due approximation, arrive at the position in space of the source of the bleeding. BPA was introduced for the first time in Italy to examine the bloodstains found on the crime scene in Novi Ligure, followed then by its second application in the case at Cogne. In the case of Cogne in particular the High Court ruled on the use of BPA techniques, establishing that they are not based on new or autonomous scientific laws, but on the application of principles that have been widely tested in past experiences, originating in other sciences (mathematics, geometry, physics biology and chemistry), and which, because they are universally recognized and applied, do not require any particular examination of their reliability. In other words, BPA techniques are based on well-known principles of physics, in particular the dynamics of fluids: it is one thing in the field of forensics, to start using an innovative application of principles that are familiar in physics, but it is quite a different problem if you try to introduce examination techniques making use of principles that are not well-consolidated or universally declared.

[2] In the cinema there is a wonderful "empirical style" reconstruction in the 1957 film "12 Angry Men," directed by Sidney Lumet.

The Strange Case of Mr. J

One evening at the end of September 2012, a young man, who we will call Mr. J for purposes of anonymity, decided to go to a bar that was about half an hour down the road from his house by car. He had neither a driving license nor his own car, and so he accepted a lift from a friend, who was, to tell the truth, more of an acquaintance than a friend. During the evening, he asked the driver to give him the keys of the car in question, saying he would wait for him there, lying down on the back seat because he was tired and sleepy. Mr. J's recollections of that evening break off at this point. There is a "hole" of many hours in his memory, from when he lay down on the back seat of the car to when he woke up tragically in the Hospital in Pisa, where he had been brought and was told by the doctors about the serious injuries he had received during a car accident. Mr. J's return to consciousness was particularly tragic above all because of the extent of his injuries: in fact the doctors have been forced to amputate his right arm. In my first meeting with Mr. J as his lawyer he showed me the official notice he had received from the public prosecutor's office stating the conclusions arrived at by the inquiry into his case: he had been charged with the crime of driving without a license. I was immediately struck by his story and by the conviction with which he kept telling me that not only had he never had a license and did not even know how to drive a car, but as he repeated over and over, he had had his friend, the driver, open the car door only because he was so tired that he wanted to lie down on the back seat. His story about his position inside the car was completely "at odds" with the serious injuries to his right arm that he had received during the accident. I kept asking myself how it could have come about that these deep lesions could have occurred in his *right* arm. In fact, the police had reconstructed the accident sustaining that Mr. J was driving the car (and therefore sitting on the left) and that, in taking a two-lane motorway junction with a bend to the right, he had lost control of the car. The front part of the car had repeatedly crashed into the guard rail on the left that divided the two carriageways and Mr. J was thrown out of the car over the guard rail, later to be found unconscious by a truck driver going in the opposite direction. According to the reconstruction made by the Police, Mr. J had hit his right arm violently against the left-hand guard rail as he was flying through the air from the car, thus receiving his severe injuries. At this point, I had many serious doubts about the conclusion reached by the investigations. The police who had arrived at the scene had too easily come to conclusions based on a process of thought that had not been demonstrated: "***But who else could have been driving the car if he was the only person to be found at the scene of the accident?***" this was what they said to me. The reconstruction with Mr. J driving the car and then thrown out against the guard rail, so I was told by the investigators,[3]

[3] The following is the reconstruction made by the Traffic Police as it emerges from the statement published in the acts of the trial (here the accused's name has been changed to protect his identity): "On 26 September 2012, Mr. J was driving Peugeot model 206 along the Aurelia state road in the direction Torre del Lago-Viareggio. When he reached the 358+200 kilometer area where the road

was, "given the circumstances" the only reconstruction possible. [...] "***In all likelihood***[4] (Mr. J) *was thrown out of the car, and, his arm was amputated when it hit against the column that connect the two bands of the guard rail in question*." Even if the accident occurred at 04:30 in the morning—this can be inferred from a call made to the sub-station of the Traffic Police—the relevant police team only arrived at the scene of the accident at 7 o'clock in the morning, when Mr. J had already been taken to hospital. My conviction, however, that something just did not tally in the reconstruction of the accident made by the police started whirling even more noisily round in my head when I had received clearance from the Public Prosecutor, and I started making a detailed study of the entire folder regarding the accident, including the measurements taken, the site plan, the notes, the short witness statements and the photos. To begin with, there was the statement made by the first person to give Mr. J assistance, a Moldavian truck driver. He had been going along the same junction in the other lane (in the opposite direction) when he noticed initially a stationary car on the right-hand side of the road which had come up against the guard rail of the opposite lane to him, and then, after a few meters, a young man who was unconscious and lying in a pool of blood on the road beside the left-hand guard rail (in the direction his truck was going) with one arm (that on the right) severely injured.

The driver stopped at once to give assistance to the young man (the first call requesting immediate emergency services was made at 04:30 in the morning). However the local emergency service was only given the alert after about an hour (and in fact the victim was admitted to casualty at 6:17). The Traffic Police only arrived on the scene of the accident at 7 o'clock in the morning. Too long a time had passed between the moment of the accident and the first survey made by the police, and at this point nothing tallied in my mind in the investigators' reconstruction, which was based on abstractions that could not be put to the test of the evidence present at the scene. As claimed investigators, their reconstruction was based in fact on their having found only an injured man, a part of the central guard rail that was

bends off to the right, because of the speed at which he was driving, which was not suitable to the characteristics of the road, he crashed the left side of the car into the guard rail placed on the left of the road. After about 12 meters from the first impact, because of the fact that he was not wearing a seat belt and that the left-hand window of the car was completely open, in all likelihood (Mr. J) was thrown out of the car, and, his arm was amputated when it hit against the column that connect the two bands of the guard rail in question."

[4] The witness for the prosecution, the Policeman, who arrived on the scene of the accident at 7 o'clock in the morning in the company of a colleague again confirmed during the hearings: "*In all likelihood,* Mr. J was thrown out of the car and over the central guard rail, ending up on the carriageway leading in the opposite direction, where he remained on the ground leaving a large blood stain. He was found there by a Moldavian lorry driver in transit in the zone (who called the emergency services, having seen a person sitting on the road with his arm almost completely detached). After the driver had been thrown out, the vehicle continued on its way, finishing up at about 68 meters from the first impact with its right side against the right-hand guard rail. From the survey, made sufficient elements were found to establish that the subject indicated was the driver of the vehicle. This accounts for the charge of driving without a license and the consequent setting up of legal proceedings in front of the Court of Lucca."

torn and stained with blood and a car that had been abandoned about 10 m ahead. On such evidence they deduced that the man had been in the car and driving it, and that he had been thrown out against the guard rail dividing the road.

There were just too many incongruences and I was convinced that the story is a little more complicated than the one the Police were telling. I also had a strong conviction that a good many explanations could be found in the documents in front of me. The evidence collected included many photographs which had been taken on the scene of the accident. Amongst those showing the car there were a couple in which it was possible to see a clearer bloodstain just under its broken back left-hand side window (Fig. 7.1, cf. evidence no. 11). Near this bloodstain there were also a series of splashes of blood. As against this, there was no trace of blood on the front side window which was unbroken. Furthermore, amongst the photos of the scene of the accident there were a number that were interesting because they showed a series of blood-stained footprints going along the white line on the left-hand side of the opposite carriageway (see Fig. 7.1, evidence no. 13). These gave me the image in my head of Mr. J who was seriously injured with blood running down his right arm onto his foot as he was walking along the opposite carriageway after having climbed over the guard rail in a state of shock looking for help. After having gone in this way a few meters along, kept on his feet, perhaps, by fear and adrenalin, he would then have collapsed to the ground at the final point where he was at last found.

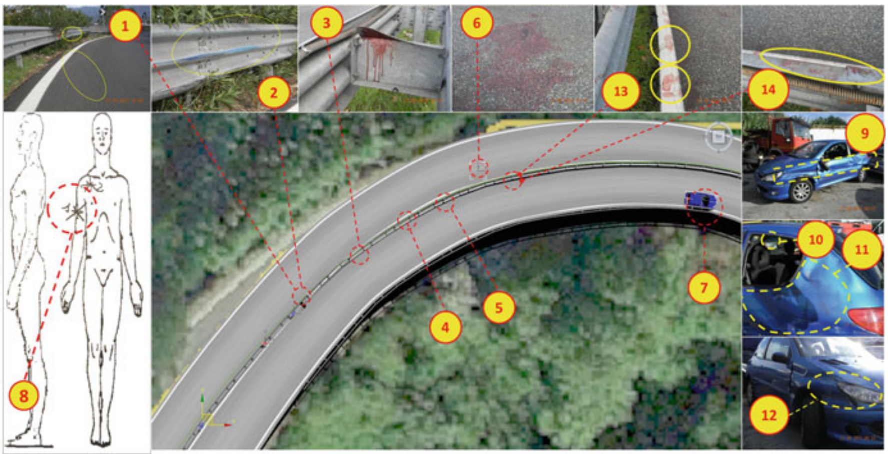

Fig. 7.1 3D view diagram of the accident reconstruction linking visual evidence (photographs) to traces identified by the Police. As can be seen from the diagram, some footprints in blood (see evidence no. 13) have been identified in the opposite carriageway along the white line near the left side of the road barrier, adjacent to the large blood stain (see evidence no. 6) On the top left-hand side of the road barrier—in the direction where the vehicle was driving—and parallel to the footprints in blood (evidence no. 13), some traces in blood of the print of the palm of a hand have been photographed

A list of all the incongruences to be found in the reconstruction made by the Police encouraged me to think more critically and analytically about what had happened:

- Mr. J had never taken out a driving license and he had never driven a motor car;
- He gave a precise description of the resting position he took up on the back seat of the car;
- The severe wound to his right arm against the left hand guard rail;
- The great number of uncertainties in the reconstruction carried out by the Police;
- The timing of the rescue services;
- The photographs of a clearer bloodstain under the back left-hand side window of the car and footprints in blood on the line marking the edge of the road on the opposite carriageway;
- Hastily written and contradictory witness statements.

I was more and more convinced of my reconstruction with Mr. J asleep on the back seat of the car in a sitting position, his right shoulder against the back side window, the nape of his neck on the back seat and his legs partially stretched out on the back seat. If we start off from this position, upon the impact of the accident his right shoulder shatters the back side window (which was, in fact, found broken, evidence no. 10 in the diagram in Fig. 7.1), and, after having made a movement that is not clear, his right hand hits against the guard rail. Only after the car comes to a halt in the position identified in Fig. 7.1 (evidence no. 7) does Mr. J get out of the car in a state of shock and go back along the opposite carriageway, until, exhausted, he falls to the ground where is later found by the truck driver. In any case, however, I was still at the starting point: how could I transform this conviction of mine into hard evidence for a judge?

I needed to be able to verify things, needed something or someone to give me a critical demonstration that the "film" in my head was the right one.

The Technique of Animated 3D Graphics and the Sequence of Events to Verify the Hypotheses of Reconstruction in the Strange Case of Mr. J

Two contrasting hypotheses need to be compared. According to the police the young man was driving, and, having lost control of the car, he crashed into the left-hand guard rail, being thrown out of the car and hitting his right arm against the central blade of the left hand guard rail. For the sake of simplicity, we will call this Hypothesis A.

Again for the sake of simplicity the hypothesis of the defense counsel will be called Hypothesis B, and in this reconstruction during the moments before the impact Mr. J is half-lying asleep on the back seat behind the car's real driver, and,

on impact with the guard rail, he breaks the back side window of the car with his shoulder while his right arm comes out of the window and hits against the column.

The method using Sequence of Event Analysis, or SEA, assisted by animated 3D graphics calls, initially, for a catalogue of all the pieces of evidence, assigning to each of them a number (cf. once again Fig. 7.1). These numbers in progression are then used to make a faithful reproduction of the accident in a virtual plane, verifying the consistency of the events with all the evidence that has been transferred into the virtual area.

The reconstruction of an accident using SEA techniques assisted by computer graphics is carried out on two levels, one static and one dynamic, rigorously developed in that same order.

The Reconstruction of the Virtual Scenario in 3D Graphics: Static Analysis

A true to life virtual replica of the accident scenario is created containing all the relevant objects that have to interact (in movement) with the set up. The stretch of road involved was therefore reconstructed (Fig. 7.1) including the guard-rail (Fig. 7.2a), the automobile involved in the accident (a model 206 Peugeot as in Fig. 7.2b) and a dummy with a physique like Mr. J's (Fig. 7.2c).

Once the scenario in question had been reconstructed with the two objects in movement (i.e. the static 3D scene) the next thing was to transpose all of the 14 previously numbered pieces of evidence onto it (see again the diagram in Fig. 1.1). It is worth underlining that "transposing" evidence means carrying out an operation that aims to transfer all the evidence into the static 3D scenario by respecting the real calculations (i.e. positions and measurements)[5] with which they have been catalogued in the original reconstruction of the accident.

The Reconstruction of the Virtual Scenario in 3D Graphics: Dynamic Analysis

The dynamic phase of the computer-assisted SEA analysis foresees, therefore, setting the objects in movement: in our case, the car and the dummy inside, following one or more hypotheses of reconstruction (here, two hypotheses have been formulated, hypothesis A and hypothesis B). All the movements recreated following a given hypothesis need to be coherent with the static scenario. For

[5] Il software used in a 3D reconstruction of the scene allows you, in fact, to establish a priori the measurements in units of the objects created and to keep to a tight coherence between their relative position both in the real and the virtual scenario.

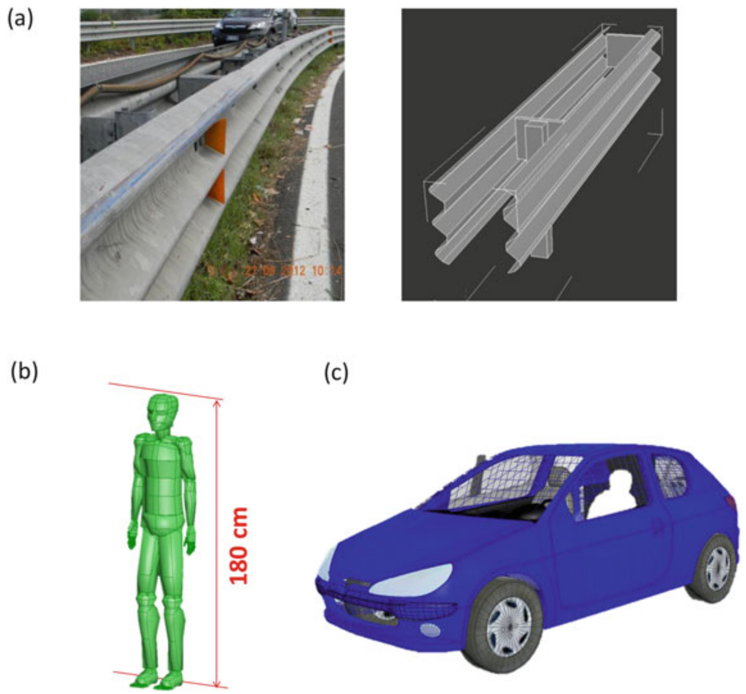

Fig. 7.2 Some details of the reconstruction of the accident scenario using SEA techniques assisted by computer graphics: (**a**) part of the carriageway, road division guard rail including the supporting columns; (**b**) dummy with Mr. J's physique; (**c**) graphic 3D replica of the automobile involved in the accident

example, the car has to move first inside its 3D graphic environment along a well-defined trajectory traced out from the information gathered on the static scene of the accident itemizing step by step the blue scratch marks on the guard rail (evidence no. 1, 2 4, 5 e 7) and taking care to verify that each impact against the guard rail could have created its "effect" (cf. evidence no. 9 e 11) on the 3D model of the automobile. These traces transposed into a virtual environment have the job of "anchoring" the movement of the vehicle in the recreated virtual scenario to the real situation as it occurred as we have seen introduced in Chap. 1 in the diagram in Fig. 1.1.

The results of these two hypotheses of reconstruction, A and B, created using SEA techniques assisted by computer graphics were then shown to the court. The two videos reconstructing the accident are available on the page www.forensicsea.com.

Verification of Hypothesis A Using the SEA Technique Assisted by 3D Computer Graphics

Keep in mind that in hypothesis A as set out by the Traffic Police, Mr. J is driving the car. During the impact against the guard rail, he is thrown out of the automobile and hits against the block of the central guardrail thus receiving serious lesions to the right arm. To verify this hypothesis, the dummy is therefore placed in the car's driving seat. At this point, the verification is carried out in its dynamic phase, moving the automobile and the dummy inside so as to respect all the pieces of evidence, that is to say, trying to make the movements of the vehicle and the dummy coincide with the greatest number of traces (i.e. pieces of evidence) as reproduced in the static virtual environment. There are a great number of incongruences and incompatibilities in the reconstruction of hypothesis A as verified using the SEA technique assisted by computer graphics:

– the movement of the dummy which needs to be thrown out of the car is completely unrealistic; under pressure during counter-examination, the police agent that had reconstructed the facts according to hypothesis A kept repeating that Mr. J, who was driving the car, had been thrown out of the vehicle on impact with the central guard rail. To find agreement with this hypothesis, Mr J would have had to extract himself from under the steering wheel with a movement that was impossible to carry out from the physical point of view because it would have involved interpenetration between his legs and the steering wheel. Moreover, for his right arm to impact against the block of the central guard rail he would have had to make, as he was flying through the air, a revolution of about 90° on his own axis and this was seen in the reconstruction video as an **unrealistic** movement in the absence of any force that could have impressed such a rotation.
– the trajectory of the car was incoherent with its final position. From the moment when Mr. J had abandoned the vehicle (cf. point 1) it would have been without a driver, and the only plausible trajectory of a driverless car along a road bending to the right if the vehicle itself is in working order and all its driving parts intact (i.e. steering wheel, shock absorbers, tires, etc.) would have been for the guard rail to have "contained" it; in this sense, it would have continued to scrape along the barrier until it came to a halt against the left-hand guardrail, in a position, therefore, that was incompatible with the discovery of the car against the guard rail on the right.
– the bloodstains visible in correspondence with the back left-hand strut of the car (Fig. 7.1, evidence no. 11), that is to say in correspondence with its (broken) back window. According to this reconstruction the man would have been injured when he had already been thrown out of the car, for which reason the blood should have been found on the guard rail, on the road surface or on the man himself, but not on the body of the car.

- the footprints in blood (Fig. 7.1, evidence no. 13) along the opposite carriageway which go in the direction of the car towards the bloodstain: the prints were clear and it was possible to recognize toe point and heel and so the presumable direction taken, i.e., from the stationary car towards the bloodstain where the person fell to the ground. Prints left by the palm of a hand covered in blood also emerged on the central guard rail (Fig. 7.1, evidence no. 14) and these made it clear that the subject had leaned on the rail with his left hand. These bloodstains were not compatible with the reconstructed made by the Traffic Police because, according to the conclusions reached in their records which were then repeated during the trial, the dummy had already been thrown out of the car a long way behind.

Verification of Hypothesis B Using the SEA Technique Assisted by 3D Computer Graphics

As in the case of hypothesis A, hypothesis B—made by the defense counsel of the accused—likewise underwent the same type of verification using the SEA technique assisted by 3D graphics. First, the dummy was placed on the back seat in a sitting position with its right shoulder leaning against the back side window and a hand holding its head, its right elbow at about the position of the opening of the window (the clip that releases the glass and leaves a slit). As emerges from the video, available on the page www.forensicsea.com all 14 pieces of evidence are coherent in this reconstruction with the movements carried out, and, further, these same movements are now physically plausible. In particular:

- The movement of the dummy. As a result of the impact of the vehicle against the guard rail, the young man, who is sleeping on the back seat leaning against the back side window is thrust towards the outside by the bend in the road as an effect of centrifugal force; his shoulder and his arms bring so much pressure to bear against the window that they break it; once the window has been broken, the centrifugal force pushes Mr. J towards the outside until he manages to regain his balance. In this phase his right arm is stretching out of the back side window, instinctively in search of a point of support. Between the smashing of the window, the external movement and the rebalancing there is the event of the right arm which is at this point nearest to the guard rail block. This movement is convincing because it is governed by physical laws (centrifugal force and rebalancing movement made by the abdominal muscles and the lower limbs);
- The trajectory of the vehicle is compatible with the fact that immediately after the impact with the guard rail the driver instinctively swerved to the right to get back his control of the car;
- The bloodstained footprints and the direction where they were going as located on the scene are compatible with the path taken by Mr. J, who gets out—or is made to get out—of the car and heads off badly injured, climbs over the guard

rail and walks along the other carriageway until he falls down exhausted on the ground where he is found by the truck driver;
- The traces of blood found on the left-hand strut of the car are compatible because, as brought about by the violence with which the arm hit against the column—remember, the man was still on board—it would have bent backwards, deforming the bodywork and staining it with the blood from the serious injury sustained;
- The impact of the car against the guardrail was violent enough to break the side window at the back. With a simple calculation based on the speed of the car and its body weight (things we know) and the variation in its direction of acceleration, we can make an approximate estimation of the thrust brought to bear by the shoulder against the glass; multiplied by the upper body mass neck, shoulder, elbow and arm) we arrive at a force of at least 250 kg suddenly impressed against the window, which, it is reasonable to think, might easily have broken.

The Judge's Conclusions

The public prosecutor was certainly taken aback by such a detailed reconstruction and could only insist that the blood should have been found on the back seat as well: a pity that the original inquiries did not go so far as to take any photographs of the inside of the car (all the photographic material made available by the consultant is the same as that in possession of the Traffic Police, who considered it appropriate to concentrate their work on the outside of the car and the footprints as we have already indicated). After the cross examination of the technical consultant, who is also the author of this book, the accused, Mr. J, was heard, and, besides re-affirming that he had not been driving the vehicle, also confirmed among other things, that he had fallen asleep in the back seat: this uncertainty about the real driver convinced the judge to adjourn the hearings to take statements both from the owner of the car and from the person the proprietor indicated as the one who had been using it. No greater certainty emerged from these depositions except that, in accusing each other, the two people who were under examination simply strengthened the reconstruction made by defense counsel.

In motivating the sentence, the judge of the court of Lucca, having evaluated the numerous incongruences which had emerged during the preliminary hearings, opted for the thesis as made by the defense counsel, underlining, in particular, how

> the breaking of the car's back side window and the evident traces of blood on the car body nearby do not allow us to consider overcome the hypothesis that Mr. J really was seated in the back of the car and was, therefore, not driving it. On the other hand, the opposing hypothesis that puts him in the driving seat presents more than one critical problem in terms of the dynamics with which he would have been thrown out, unless we are to believe, without being able to explain the mechanism with which such a thing could have taken place – incompatible as it is with the size of the car's passenger compartment – that Mr. J's arm was amputated after his body had turned upon itself as he was being thrown out of the driving window.

The Integration of SEA with 3D Animated Computer Graphics: The Viareggio Railway Accident Reconstruction

In the case of an industrial accident of huge proportions the scene to be analyzed is clearly more complex than the one we have just been looking at, involving Mr. J. Nevertheless, nothing changes in the methods to be used in setting up the SEA analysis assisted by computer graphics. In the specific case here in question, you need to consider the vast quantity of information obtained during the investigations on the scene of the accident, which all need to be transposed onto the static 3D scenario. A further complication consists in the difficulty there is in faithfully reproducing relevant parts and objects in 3D computer graphics. You must consider, however, that in the case of more complex accident scenarios of huge proportions—just like the accident we will be speaking of in a moment—3D *engineers* are given aid by 3D scanner techniques which are often used in the creation of the static 3D scene to import objects, parts and important elements to scale and size and in their real post-crash morphology. We could say further that law courts began to realize some years ago how important tridimensional scansion[6] really is from the point of view of an inquiry, as it allows us on the one hand to "freeze" the positions of the traces present in the area, and, on the other, it simplifies the job of the technicians working on the subsequent reconstruction of the scenario.

Let us now return to the case of the railway disaster that occurred on 29 June 2009[7] in the station of Viareggio, Italy, with which we wished to begin this book.

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[6] 3D laser scanning without contact and at high speed is an ultra-modern device which is at present used for measuring and documenting objects in 3D. It is able in a few minutes to generate clouds of points (millions of points reproduced in absolute X, Y, Z co-ordinates) that can form accurate virtual images of objects and their volumes in 3D. Applications using this technique range from 3D land survey reconstruction to the designing of plants and factories in the building and architectural field and restoration on works of cultural importance, from mechanical design using *reverse engineering* techniques to oral and maxillofacial surgery and so on, right on down to its most recent applications in forensic science (virtual reconstruction of the crime scene, reconstruction of the trajectories of bullets, etc.). High definition 3D laser scanning of a crime scene is used as the first step towards obtaining a tridimensional reconstruction of the dynamics of the criminal event. In this way the crime scene can be looked at from different perspectives to check, for example, the reliability of a deposition, or the trajectory of a body in transit on the scene in movement (e.g., bullets, drops of blood, vehicles). New technology high precision 3D scanners have recently been released on the market which can for the first time carry out a survey of the surfaces in an absolute positioning survey system (using GPS), that is to say, a system capable of surveying vast scenarios using the automatic re-composition of the single areas surveyed inside the range of the instrument.

[7] The Viareggio Railway Accident was a railway disaster that took place on 29 June 2009, at 23:48 CEST. It occurred after the derailment of freight train 50325 which was transporting 13 tank cars containing Liquid Petroleum Gas (LPG). The derailment was caused by the breakage of an axle on the first tank car. Because of the derailment the first tank car fell on its side along the railway line and then impacted with an element present there. This impact tore a hole in the tank and thus the leakage of the gas contained in this first car. An immense fire then broke out involving the houses near the railway line and causing the death of 32 people, many of whom were sleeping in their beds.

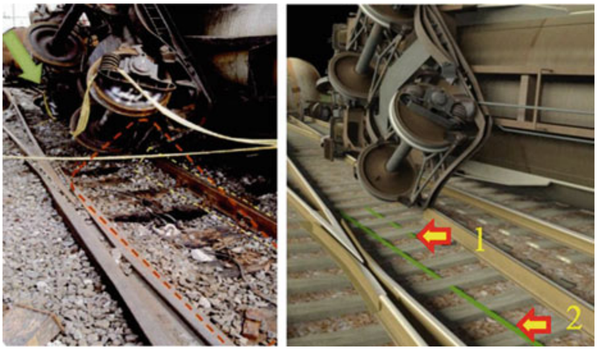
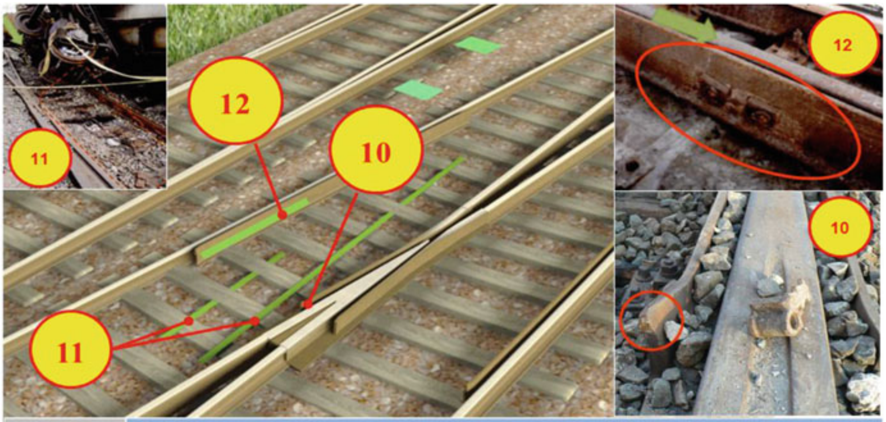


Fig. 7.3 Real image (photo a) taken by Forensics compared with the 3D reconstruction (photo b) created in a virtual environment

Beginning with the photographs,[8] the videos and above all the measurements carried out on the scene of the accident by Forensics and the Judiciary Police we managed to identify the position and nature of many objects that had broken off the tank cars making up the railway convoy after the movements (clearly unknown) that finally put them into their final immobile layout, which was of course evident from the numerous photographs taken and the measurements immediately made on the day subsequent to the accident. All damage reported to the different parts of the infrastructures were catalogued and photographed, and this information was essential to the 3D reconstruction of the static scenario. One example is shown in Fig. 7.3: the image on the left is one of the numerous photographs taken by Forensics the morning after the accident; instead, the picture on the right shows the same subject reproduced after having reconstructed the 3D scenario of the accident and having positioned the derailed convoy in the exact same position determined both by the photographic documentation and the measurements supplied by Forensics and the Judiciary Police, who carried out the inquiry.

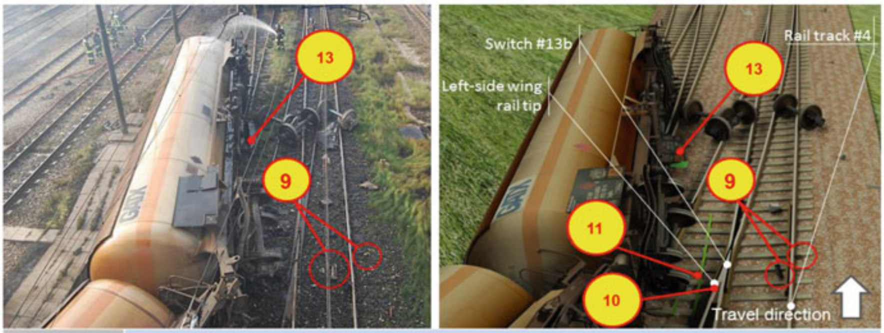
In particular, the *traces* present on the sleepers, clearly visible in Fig. 7.3a, were useful from the point of view of the reconstruction of movements made by the derailed tank cars. Once these signs had been put into the accident scene that had been created in virtual 3D graphics (cf. strips 1 and 2 in Fig. 7.3b), they were then used to determine in detail the position of the tank car that had transited over them during its final movement. Apart from the two signs given in Fig. 7.3b, this

[8] At the time of the accident 3D laser scanning was not carried out on the area of the accident. This scanning technique was only introduced later by the Public Prosecutor's consultant. If, on the one hand, the authors of this book would like to point out that 3D scanning of the area of an accident should always be made as a fundamental, priority step immediately after an accident by any Prosecutor that is conducting an inquiry and that it should be executed immediately after the accident, it is, on the other hand our duty to point out that such techniques were never taken into consideration in Italy before the case of Viareggio because they were not popular even in the international field. In the United States, the *s* only began to publicize information bulletins for its members in 2012, where they introduced and described the potentialities of 3D laser scanning techniques applied to the reconstruction of road accident scenes and other crime scenes that were particularly complex, involving mortal cases of gunfire.



No.	Evidence
10	Signs of damage on the **left-side wing rail** and deformation of the tip of the wing rail
11	Marks on the **wood sleepers** nearby the switch No. 13b
12	Signs of wear left by metal part that slid on the **left-side check rail** and some fasten bolts broken

Fig. 7.4 Detail of the transit zone of the derailed convoy reproduced in a virtual 3D scene showing the key evidence found on the real scene by Forensics and the Judiciary Police



No.	key-evidence
9	Signs of damage on the check rail (switch No. 13b) and No. 2 broken parts of the No. 1 right-side journal box
11	Signs on the wood sleepers nearby the switch No. 13b
10	Signs of damage on the wing rail and deformation of the tip of the wing rail
13	Broken part of the chain coupler linking wagon #1 and wagon #2

Fig. 7.5 Another detail of a different transit zone of the derailed convoy reproduced in a virtual 3D scene showing the key evidence found on the real scene by Forensics and the Judiciary Police

particular zone was very “dense” with further (*key evidence*) traces. Figures 7.4 and 7.5 have a special place in the 3D reconstruction of the area in question, allowing for the re-positioning of the *key-evidence* produced by the investigators.

No.	Key-Evidence
9	Signs of impact on check rail 13b and parts of the axle spring plank
10	Signs of impact on the frog or common crossing and the frog's point of deformation
11	Signs on the sleepers on a level with the points switch
12	Scraping signs made by a metallic part inside the left-hand check rail (direction of train) and bolts torn apart

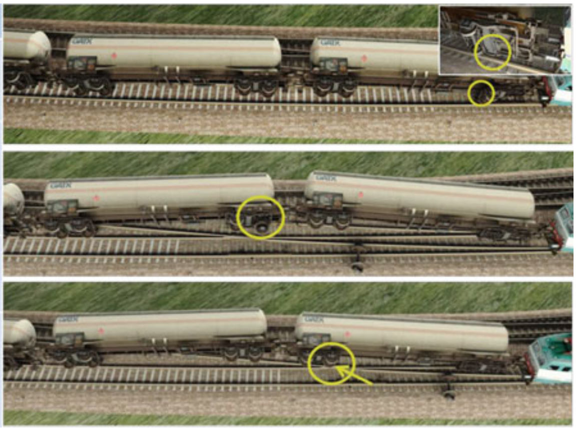


Fig. 7.6 Reconstruction of detailed position of the convoy

For example, the trace left by a part of the wheel set belonging to tank car 1 as it passed in transit here (cf. *key-evidence* no. 9 in the table given in Fig. 7.5) gave precise information about the point of impact between a well-determined part of tank car 1 (the axle box spring plank, see the detail inset in image 2, Fig. 7.5) and a precise point in the infrastructure. This, in its turn, allowed us to position the 3D model of tank car 1, which is a faithful reproduction of the real tank car, as it was in transit over the area shown in Fig. 7.3. Once this position was known, we went on to move tank car 1 forward along with tank car 2 which was attached to it to determine the new position taken up by the two tank cars as shown in image 2, Fig. 7.6.

Moving tank cars 1 and 2 forwards from this last configuration, we can therefore reconstruct the path of some particulars belonging to their lower structure (frame and bogie), which interacted with the railway infrastructure at a number of specific points; that is to say, the interaction between these objects and the railway track area allowed us to explain the presence of *key-evidence* points nos. 9, 10, 11 and 12 (cf. Table 7.1), which had been found on the scene of the accident.

Using these positioning techniques as illustrated above enabled us, during the second "dynamic" analysis phase, to explain the presence of all four points of *key evidence*, nos. 9, 10, 11 and 12, reconstructing the sequence of events frame after frame. It is interesting to note how the subsequent verifications that were made gave the proof that no other "transit" configuration put forward (i.e., no other sequence of *key-events*) can explain all four points of *key evidence*. In other words, the *key-evidence* present in this area makes it possible to "qualify" this reconstruction (sequence of events 1-2-3 as reported in Fig. 7.6) as a ***consistent*** reconstruction of *key-events*.

Table 7.1 The summarizing table showing evidences demonstrated by: (a) the hypothesis A, (b) the hypothesis B as presented in the Court

(a)

Key-evidence	Description	Consistency
1	point of impact	verified
2	blue strip on the left of steel road barrier	verified
3	traces of blood on the bracket	verified
4	blue strip on the left of steel road barrier	verified
5	blue strip on the left of steel road barrier	verified
6	Great bloodstain	not verified
7	Breakpoint / blue strip on the right of steel road barrier	not verified
8	Injury point onto rigth arm	subjected to irrealistic movements
9	traces on the left side due to the impact against the steel road barrier	verified
10	left rear window broken	not verified
11	wide deformed zone with conspicuous blood spots (projected in the direction of the wind)	not verified
12	signs of an impact against the road barrier onto front (right side) of the car	not verified
13	bloody footprints	not verified
14	bloody handprints	not verified

(b)

Key-evidence	Description	Consistency
1	point of impact	verified
2	blue strip on the left of steel road barrier	verified
3	traces of blood on the bracket	verified
4	blue strip on the left of steel road barrier	verified
5	blue strip on the left of steel road barrier	verified
6	Great bloodstain	verified
7	Breakpoint / blue strip on the right of steel road barrier	verified
8	Injury point onto rigth arm	verified
9	traces on the left side due to the impact against the steel road barrier	verified
10	left rear window broken	verified
11	wide deformed zone with conspicuous blood spots (projected in the direction of the wind)	verified
12	signs of an impact against the road barrier onto front (right side) of the car	verified
13	bloody footprints	verified
14	bloody handprints	verified

From different points of view, the animated 3D graphic on home page www.forensicsea.com shows the movements of the tank cars as they interact dynamically with each other and with the infrastructure. At the top of the screen there are colored indicators which go one after the other from red to green as the scene is played out (Fig. 7.7): this happens at the precise moment of the occurrence of a *key-event* which can give a causal "explanation" for the presence of one of the **16 pieces of evidence** gathered by the investigators on the scene of the accident which have been reported in brief (so that they can be easily read) in Table 7.2 as precisely positioned in the 3D static environment (see page on the Viareggio Railway Disaster Accident Recnstruction, at www.forensicsea.com).

The rigorous application of SEA techniques assisted by animated 3D graphic reconstruction enables us to "explain" all the pieces of evidence gathered at the scene of the accident using a precise sequence of key events that reconstruct the railway disaster in Viareggio.

Table 7.2 List of all the pieces of evidence collected on the scene by the Police and Forensics

N. ro	Key-evidence (traces) gathered by the Police	Key-event
1	Mounting trace	The flange of the front right-hand wheel on tank car 1 begins to mount the right hand railway track (direction of train)
2	Derailment point, signs on the internal side of the sleepers of the left-hand track (direction of train)	The first wheel set on tank car 1 begins to swing to the right; from the signs made by the flange of one single wheel on the inside part of the left-hand track's sleepers we can deduce that from this point onwards the left-hand wheel of the first axle falls onto the sleepers; the one on the right is about to impact (see later) together with its journal box against the curb of the platform, while the second axle is still regularly in position on the tracks (there are no further traces left by wheels on the sleepers in this zone).
3	Impact of the wheel set against the platform curb	The right-hand journal box, wheel set 85890 (first axle), impacts against the platform curb and from this moment onwards it will continue to scrape in various places against the curb; the curb itself keeps the tank car, which has at this point derailed, in an upright position. The second axle of the first tank car's first wheel set is still in position on the tracks. The back wheel set of tank car no. 1 is regularly positioned on the tracks.
4	The flange of the wheel leaves a trace on the ramp leading down to the ground level crossing	The right-hand wheel of tank car 1's first axle (wheel set 85890) is no longer supported by the curb and deviates to the right into the opening leading as a ramp down from the platform towards the ground level crossing. The wheel begins to ascend this ramp.
5	The edge of the platform begins to be broken after the ground level crossing	The right-hand wheel of the first axle (wheel set 85890) on tank car 1 bears its weight down on the edge of the platform and begins to break it.
6	The end of the zone where the kerb is broken up	At present, the right wheel of tank car 1's first axle (wheel set 85890) moves upwards. The opposite wheel on this wheel set, 85890, begins to cut into the sleepers and now the whole wheel set turns suddenly in an anti-clockwise direction, now leaving wheel set 98331 unhitched. This rotation of the wheel set increases tank car 1's overturning movement: its barycenter goes out of kilter, setting off the phase of complete capsizing.
7	2 signs of impact on the platform curb	While wheel set 98331 is thrown by the rotating movement of the wheel casing (cf. point 6) the flanges of the right and left wheels impact against the edge of the platform, leaving two breakage signs.
8	Plowing zone where a portion of the right-hand track (direction of train) is lifted upwards	Once the no. 1 bogie has begun to rotate—because of the cutting down movement of the first left-hand wheel, set 85890 (cf. point 6)—the sleepers begin to be broken up (plowing zone) and get

(continued)

Table 7.2 (continued)

N. ro	Key-evidence (traces) gathered by the Police	Key-event
		piled under the right hand track (direction of train) while at the same time and for a certain distance (until, that is, the bogie stops rotating) this track is prized upwards.
9	Signs of impact on check rail 13b and parts of the axle spring plank	The check rail enters into frontal impact with wheel set 85890's right-hand journal box: we can be sure that this deduction is correct because to the right and left of the left-hand track (direction of train) just after the check rail begins to be broken there are two parts of the axle spring plank belonging to this journal box. Only the first bogie of tank car no. 1 passes this point. After impact, the bogie begins its second rotation.
10	Signs of impact on the frog or common crossing and the frog's point of deformation	An object impacts against the frog. From the 3D graphic reconstruction, having positioned tank cars nos. 1 and 2 correctly, it is possible to pick out that this is the axle box belonging to the first axle of tank car 1's second bogie.
11	Signs on the sleepers on a level with the points switch	There are signs of scraping on the wooden sleepers. From the 3D reconstruction it is possible to identify the object that leaves these signs on the sleepers close to the frog as the first axle of thee back bogie.
12	Scraping signs made by a metallic part inside the left-hand check rail (direction of train) and bolts torn apart.	The reciprocal position of tank cars nos. 1 and 2 (coupled together) means that in passing the front bogie of tank car no. 2 will impact and scrape against the internal face of the left-hand check rail (direction of train). At the same time the heads of some of the bolts keeping the check rail anchored are torn apart.
13	Position of the back coupling of tank car no. 1	Tank car no. 2's progress is impeded by the left hand check rail (cf. point 12) while tank car no. 1 continues to be dragged forwards by the locomotive. The front of tank car no. 2 is not able any longer to follow the movement made by the back of tank car no. 1: the hitching organ (coupling) between cars nos. 1 and 2 gets torn off.
14	Picket no. 24 is knocked down	Tank car no. 1 moves ahead—coupled to the engine and uncoupled (cf. point 13) from tank car no. 2—towards picket no. 24 impacting with it at the point in correspondence with where the laceration begins in the tank.
15	Signs of impact on the body at the back of the engine; the engine and tank car 1 uncouple	During the collision with picket no. 24 (cf. point 14) tank car no. 1 slows down and is rammed (buffer against buffer) by tank car no. 2 (already uncoupled, cf. point no. 13). This forward thrust makes tank car no. 1 collide with the train engine (buffer against the body of the locomotive). Tank car no. 1's movement of rotation (movement of the back of the car towards the left) has already initiated and this, in combination with its forward movement, brings about the uncoupling (sliding out from the hitch) of tank car no. 1 from the locomotive.
16	Picket no. 23 knocked down	The back of the tank car impacts with picket no. 24, knocking it over.

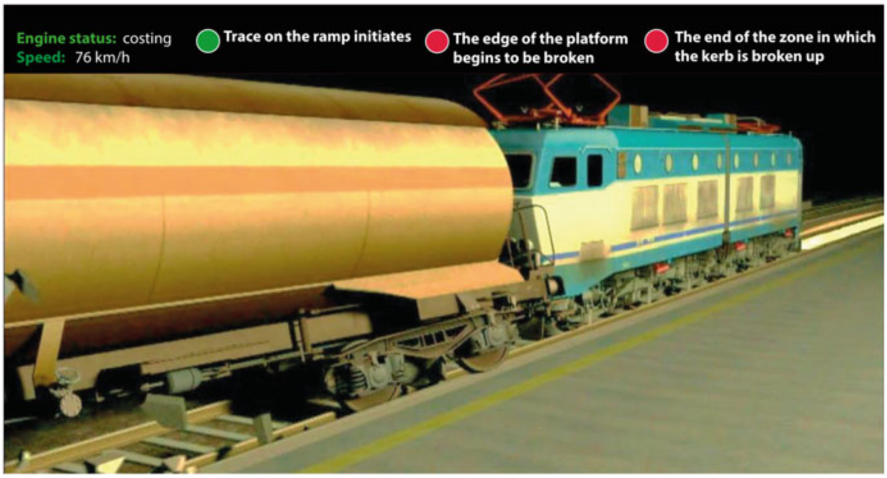


Fig. 7.7 Example of a film frame from the animated 3D reconstruction of the accident showing at the top the timed indicators that change color from green to red every time a trace is covered by the movement of the convoy

The Hybrid Technique, 3D Scanner and Computer Graphics

Many details of the accident were reconstructed in the presence of the Court of Lucca. It was necessary to put the three judges in a position to understand and make independent verifications on the precision of such details in reconstruction, and so a hybrid technique was used for the first time, which consists in reproducing the dynamics[9] of a particular event—for example, the penetration of an element belonging to the railway line into the tank of the tank car—in an animated 3D graphics environment using as the two objects in the phase of interpenetration, their own surfaces directly obtained by 3D scanning of the objects themselves found on the scene of the accident. Specifically, the static 3D scene was given finishing touches by the *3D graphic engineer* when he perfectly “fitted” the upper portion of the picket—which had been digitalized and catalogued by the investigators with 3D scanning so it could be used as evidence—right onto the top of picket no. 24.[10] In the same way, the 3D graphic engineer applied the 3D scan carried out on the laceration onto the portion of the surface of tank in question that was actually gashed in this way. This completed the phase of static analysis that was necessary to put detailed finishing touches on the whole “laceration of the tank by picket no. 24” sequence, which had to be reconstructed and verified using the SEA technique in a

[9] The correct term in the technical language in this field is “kinematics” of movement rather than “dynamics.” However, such a distinction is not really relevant to the purposes of the more legally based reader of this book.

[10] This was the element responsible for puncturing the tank in the hypothesis of reconstruction of the events made by the authors of this book.

3D graphic environment. The 3D graphic engineer then "animated" the sequence of the scene, which includes the (practically simultaneous phases of: (1) the knocking over of picket no. 24; (2) the partial burying of the picket into the ground and its own ballast; and (3) the incision and laceration of the surface of the tank creating the gash. As we have already seen in the simplified case involving Mr. J, it is again necessary in this dynamic sequence to have a number of sure and certain "anchoring points" that are able to impose—amongst all the great number of different but plausible (i.e., coherent) movements—the only one that can faithfully reproduce the unique movement that really occurred. We have seen that in Mr. J's case these points of "anchorage" were the various traces (i.e., the pieces of evidence) present on the static scene, for example, the traces of blue paint found on the guard rail and the dents on the left-hand wing of the car. These were utmost important during the dynamic phase to reproduce the car's trajectory in a 3D environment. In this specific case, however, there was a lot of "information" that could be used. First, it is possible to establish with certainty both the initial (picket upright at a known distance from track no. 4) and the final position. In particular, its precise final position was faithfully recreated in a virtual environment based on the measurements carried out when the position picket of no. 24 was actually found (see the multimedia document "included in video "Chapter 3" at minute 2' 21", the "Evidence n.17 - The coupling morphology of opposing elements forming the cut and the relative kinetics of the cutting" on page www.forensicsea.com). Also the scratch marks present on the two opposing surfaces—the top of picket no. 24 and terminal portion of the laceration—were totally important. Such evident signs are abrasion marks of reciprocal scraping between two metallic surfaces that had entered in contact. These scratches were reproduced initially in a 3D graphic environment on the scanned surfaces of the two opposing objects and then subsequently used to "guide" the top of the picket along its passageway on the surface to the precise point where the laceration was made in the tank. As is evident in the multimedia document "Kinematics of the laceration of the tank," the scratches on the two surfaces line up in the direction of relative movement as must normally occur when any two surfaces "chafe" one against the other. Another "obligation" that was imposed during the kinematic reconstruction of the laceration was to verify *frame* by *frame* (i.e. millimeter after millimeter along the edge of the gash) that the cutting surface of the picket was in perfect contact with the lateral surfaces of the laceration produced: as can be seen in the multimedia document, the picket starts out in an upright position but finishes partially buried in the ground in a rotated position. It is this frame by frame reconstruction of the rotation that verified the "consistency" of the relative movement between the two inter-penetrating objects both regarding the scratches we have mentioned and the compatibility between the lacerating edge at the top of the picket and the gash in the steel plating of the tank that was cut open.

The Last Frontier of Assisted SEA Analysis: Dynamic Hybrid Analysis in 3D Graphics and Its Verification Using Dynamic Multibody Analysis Software[11]

In this last section we wish to put the reader in touch of the last frontier with which we have been involved. The basic idea is to try and get across the limits contained indistinctly in all multibody system simulations (among which, as an example, the famous Adams software by MSC Software Corporation used in our work as given here). It is our primary duty to point out that this limitation is not something created by the software in itself because the degree of "precision" and reliability with which these codes permit the simulation of complex systems in movement, faithfully reproducing their dynamic behavior is now evident to everyone working in the field of engineering. The limitation, in fact, is general to all simulation codes in cases where they have to be used, not in the planning phase (i.e. when a complex system is modeled and simulated in the different possible conditions which have been noted and assigned to it so as to test its reliability, for example) but during verification that the hypothetical movement is—among the infinite possible sequences of events—actually the single sequence that really did occur. The fact itself that these are infinite explains how it is impossible to know: (a) what all the parameters are that need to be imposed on a code of this type, and (b) how to assign detailed values so as to put the multibody system "in transit" along all the traces present on the static 3D scene.

It is worth pointing out before we go on—running the risk of giving our readers information that might even seem superfluous—the difference between a "kinematic" type and a "dynamic" type study of the movement of any body (or complex system). The kinematic study of a body (or system of bodies) involves resolving the problem of how to define the movements of this body in a way that is compatible with the surrounding "constraints," while studies on the dynamics of the same body entail analyzing not only how the movement is possible in connection with the constraints, but also how it is "governed" by valid theories of physics in a gravitational field, obeying the laws passed down to us by Newton and his successors. To understand the difference, imagine a marble that is rotating round a pole to which it is attached by a string: studying its kinematics means establishing the trajectory (circular, considering the presence of the string) of the marble, which should be imagined as having no mass, what is the "form" (i.e., equation) of is tangential speed, and so on. Studying its dynamics consists primarily in assigning its effective mass to the marble and then calculating how its speed assumes a certain value in function of the forces acting on it from its inertial force to the centripetal force

[11] ADAMS (Automated Dynamic Analysis of Mechanical Systems) is a multibody dynamics simulation software equipped with numerical solvers produced by MSC Software Corporation. Adams has proven essential to VPD (Virtual Prototype Development) by reducing product time to market and product development costs in engineering design in various sectors, from aeronautics to automotive.

offered by the tension of the string, etc. All this allows us to specify that the reconstruction of the movements of the tank cars using the SEA technique assisted by 3D computer graphics takes place in kinematic conditions, that is to say, by considering the compatibility between the movements reproduced and all the constraints, but not the dynamics (the bodies in movement have speed and acceleration, but the forces acting on them are not known). If, on the one hand, a computer graphics assisted SEA does not, as it has been devised, normally need dynamic analysis—it reconstructs the kinematics of the system's movements by verifying their coherence with all the available traces—there can be cases in which it is necessary to "quantify" the movements of the bodies after having reconstructed them kinematically using SEA methodology assisted by computer graphics. This was what was carried out by the authors using a hybrid *3D graphic animation* technique and a simulation with the Adams multibody software by MSC Software Corporation.

The method used can be seen on page www.forensicsea.com and it is described here in synthesis. The static scenario—which had already been carefully explored using 3D graphic assisted SEA analysis—was first brought into the Adams environment. The studied scenario regarded in particular a part of the tank car's movement through the scene, and this was simplified to facilitate its representation in 3 "control" positions. That is to say, these 3 positions correspond to 3 spots "extracted" directly from the simulation created using the SEA technique in a 3D graphic environment. The dynamic model was subsequently defined in an Adams environment, assigning its real mass to the body, its non-interfusion with the static scene (i.e. the railway layout) and some known parameters of movement (e.g., speed, de-acceleration) which had been found in the on board Data Recorder (the Driving Information System, DIS). The remaining, unknown parameters, for example, the direction and forces exchanged with other bodies belonging to the system (e.g., the locomotive or the tank car coupled behind) are the undetermined variables of the system which we need to define to "resolve" the movement in dynamic terms. At this point, the Adams software gives support to the 3D graphic engineer because it enables him to "resolve" the movement during subsequent interactions that modify the variables of the system within a certain *range* and to attempt to optimize the solution. In our specific case, this enhancement consisted in verifying the presence of a set of physical variables so as to "satisfy" the detailed positions earlier obtained on computer graphics. In non-technical language, we could say that, by making targeted attempts, we try to see if we can find the "dynamic" solution offered by the multibody system which is in strict agreement with the reconstruction of the kinematic movement created using SEA, and which already concurs, therefore, with all the traces transposed on the static 3D scene. The compared solution between the two simulations can be clearly seen in the multimedia document present at page www.forensicsea.com (refer to video "Chapter 6" in the section "The Viareggio Railway Disaster Accident Recstruction"). In this case it is therefore possible to conclude beyond all reasonable doubt that the movement of the tank car both satisfies the kinematics, consisting in the traces as located on the scene and has been resolved from the point of view of its dynamics, which are consistent with those same traces.

Conclusions

This chapter finally concluded what we left to finalize our work, as it was presented in two editions, 2012 and 2013, of Advanced Accident Reconstruction Special Seminars organized by the US National Academy of Forensic Engineers. First time we joined American colleagues in San Diego was the occasion to illustrate for the first time the method we had been developing for 3 years, from 2009 when we authors started to work as attorney and technical expert on big Viareggio railway accident. The 2012 was the occasion to introduce to American colleagues, forensic engineers, the basics of Sequence of Event Analysis. Such a method had actually allowed the attorney and the technician to start to understand each other using a comprehensible common language. Too far was the distance in law and technical fields because of different languages and ways of reasoning.

During second edition we participated as instructors in Minneapolis in 2013, the SEA applied to 3D graphic assisted accident reconstruction was illustrated. It was the occasion to reason on back to home transatlantic flight that we had to make the last job: integrating the 3D animation graphics SEA with modem technique of 3D scanner and multibody software.

Our 2-years recent efforts on that matter are here presented, and we think we finally did our job.

Some tools that you can use and customize are now available on www.forensicsea.com, so it is now on your own consciousness to put your own efforts and do the best you can to go beyond any reasonable doubt.